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COMSTAR SATELLITE 19/29 GHZ PROPAGATION EXPERIMFNT.(U)
AUG 81 S C BLOCH, D DAVIDSON, D D TANG DAAG29-77-G-0224
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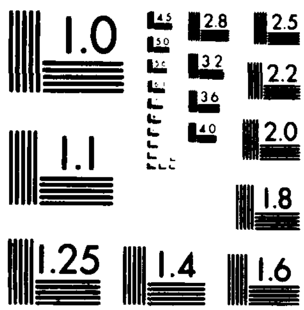

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Satellite propagation, rain attenuation, diversity performance

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Results and analysis are presented for the 19/29-GHz satellite propagation experiments using beacons aboard the COMSTAR series. Emphasis is on diversity performance of the Tampa, Florida, Triad and single-site attenuation distributions in intense rain, and on single-site performance at Waltham, Massachusetts. The substantial data base evolved to show a flattish tail on distributions due to rapid rate-of-change at onset and recovery; this type of distribution found in the Tampa rain environment was not found in Waltham.

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USF-PPL-45

COMSTAR Satellite 19/29 GHz
Propagation Experiment

Final Report

S. C. Bloch
USF

D. Davidson
D. D. Tang
GTE

August, 1981

U. S. ARMY RESEARCH OFFICE
Grant DAAG29 77 G 0224

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont.)

SECTION 1
INTRODUCTION

This report presents and discusses the results of the 19/29-GHz downlink reception experiments conducted by the University of South Florida and GTE Laboratories using beacons aboard the COMSTAR series of domestic satellites. The emphasis of this study is on diversity performance of the Tampa Triad and single-site attenuation distributions in the intense rain environment of Tampa, Florida, and on single-site performance at Waltham, Massachusetts, the location of GTE Laboratories.

The Tampa Triad comprises three receiving terminals, designated U, L, and S, (Figure 1-1). U is the University of South Florida, where a full two-frequency terminal is situated; L is Lutz, and S is Sweetwater, both exchange buildings of General Telephone Company of Florida. Deployment of the Tampa Triad was made possible through agreements between these two entities and GTE Laboratories. The baselines so formed are: LU, 11 km; SU, 16 km; and LS, 20 km. Terminals L and S record only the 19-GHz "vertical" polarization transmission, and it is on the basis of this 19-GHz reception at the three sites that diversity performance has been measured.

Tampa's rain is almost entirely composed of summer thunderstorm rain. The National Climatic Center's Bulletin, Local Climatological Data, says of Tampa (28^0 N, 82.5^0 W): "On the average, the station has near 90 days with thundershowers occurring mostly in the late afternoons of June, July, August, and September. The resulting sudden drop in temperature from about 90^0 to 70^0F induces an agreeable physiological reaction. Between a dry spring and a dry fall, some 30 inches (about 60 percent of the annual) of rain falls during the four summer months." Since our experience with the Tampa Triad has shown that May was also an important rain-producing month, the summer season has been taken for our purposes to comprise all five months.

Data collected through most of 1978 was based on reception of the D-2 satellite beacon positioned at 95^0 W. On August 24, 1978, reception was transferred from D-2 to D-3, positioned at 87^0 W, as D-2 beacons were to be shut down to conserve spacecraft battery life. the difference in elevation angle is relatively small at all receiving terminals, particularly at Tampa, where the shift was from 54.5^0 to 56.9^0, making it easy to merge data from the two periods. At these high elevation angles in Tampa, the observed rain attenuation tended to be nearly coincident with local rain occurrence as measured by a rain guage at the terminal.

A fourth terminal, exactly like the one at U, has been operated at GTE Laboratories at Waltham, Massachusetts (42.4^0 N, 71^0 W), in a totally different rain climate, (Figure 1-2). Again, quoting from the related publication of the National Climatic Center for nearby Boston: "Boston has no dry season. For most years the longest run of days with no measurable precipitationdoes not extend much more than two weeks. . .Most of the rainfall from June to September comes from showers and thunderstorms." Boston reports around 20 thunderstorm days per year, on average. Generally, but not always, the major sources of intense rainfall of interest to satellite communicators are a few, short but severe, thunderstorms. Exceptions can occur during coastal storms ("Northeasters").

The COMSTAR D-3 beacon was shut down on August 31, 1980 to conserve batteries. COMSTAR D-4, launched in February, 1981, carries a beacon that is facilitating measurements during summer 1981.

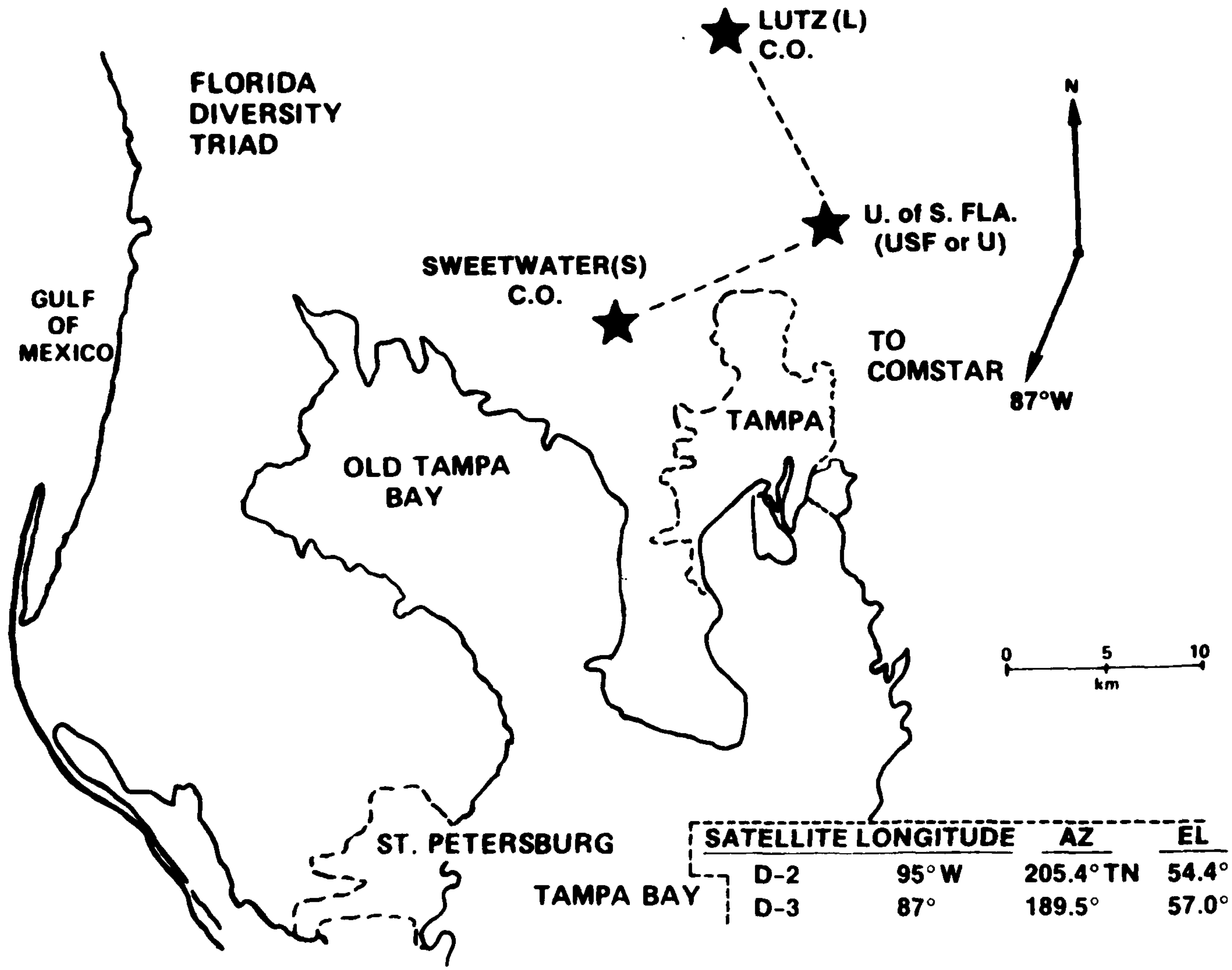


Figure 1-1. Location and Geometry of the Tampa Triad

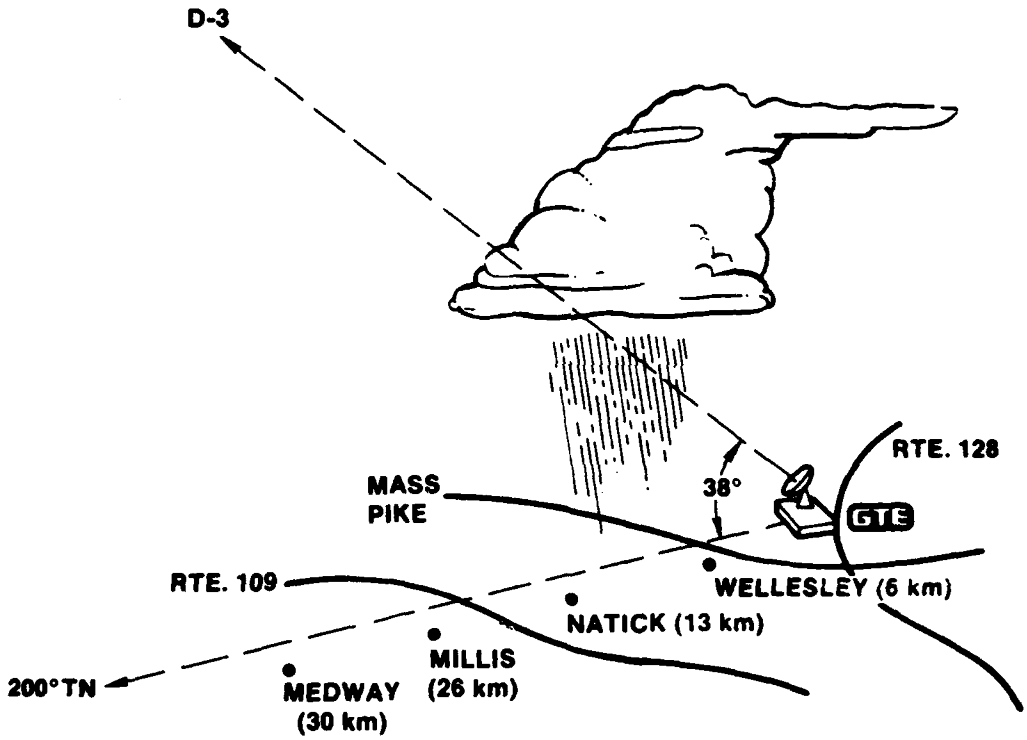


Figure 1-2. ›cation GTE Laboratories Showing Propagation Path
˛ ˛ ›MS⁷ ˛ D-3 Satellite

SECTION 2

19-GHZ ATTENUATION DISTRIBUTIONS, TAMPA

Attenuation exceedance distributions are presented for the three single sites and for the various diversity combinations. To facilitate comparison between sites and of diversity performance, all seven possible distributions are generally plotted in the same figure for the time period under consideration.

Figure 2-1 shows distributions for calendar year 1979; Figure 2-2 is for the five rainy months only (summer); Figure 2-3 gives the distributions for 1980, from January 1 through August 31 (D-3 beacon shutdown). Figure 2-4 shows the results for the four rainy summer months available to the experiment in 1980.

Several observations can be made about these distributions:

1. Over a long period, such as the group of summer months, the single-site distributions are very similar, indicating that whatever their differences in individual months, they tend to "catch up with each other."
2. The shortest pair LU is the worst diversity performer, but although for the time period covered here, the longest pair LS appears to be the best performer in that its distributions in the referenced figures always lie lowest of the three pairs, the pair SU also performed well.
3. During the five rainy months of 1979, the outage time at a given attenuation level is about twice that in the yearly distribution.
4. Application of a satellite link as a unit trunking link in a domestic telephone system requires that the propagation unavailability be less than or equal to 0.01% on an annual basis, as defined with reference to a channel noise allowance or a stated bit error probability, apart from other considerations. This objective cannot be satisfied for Tampa, judging from the results reported here, for an attenuation range of 10 dB. (10 dB is the fade margin for which system sizing is practical. See Appendix for a full discussion). It appears that such an objective can only be met in Tampa at 19 GHz with three-site diversity.

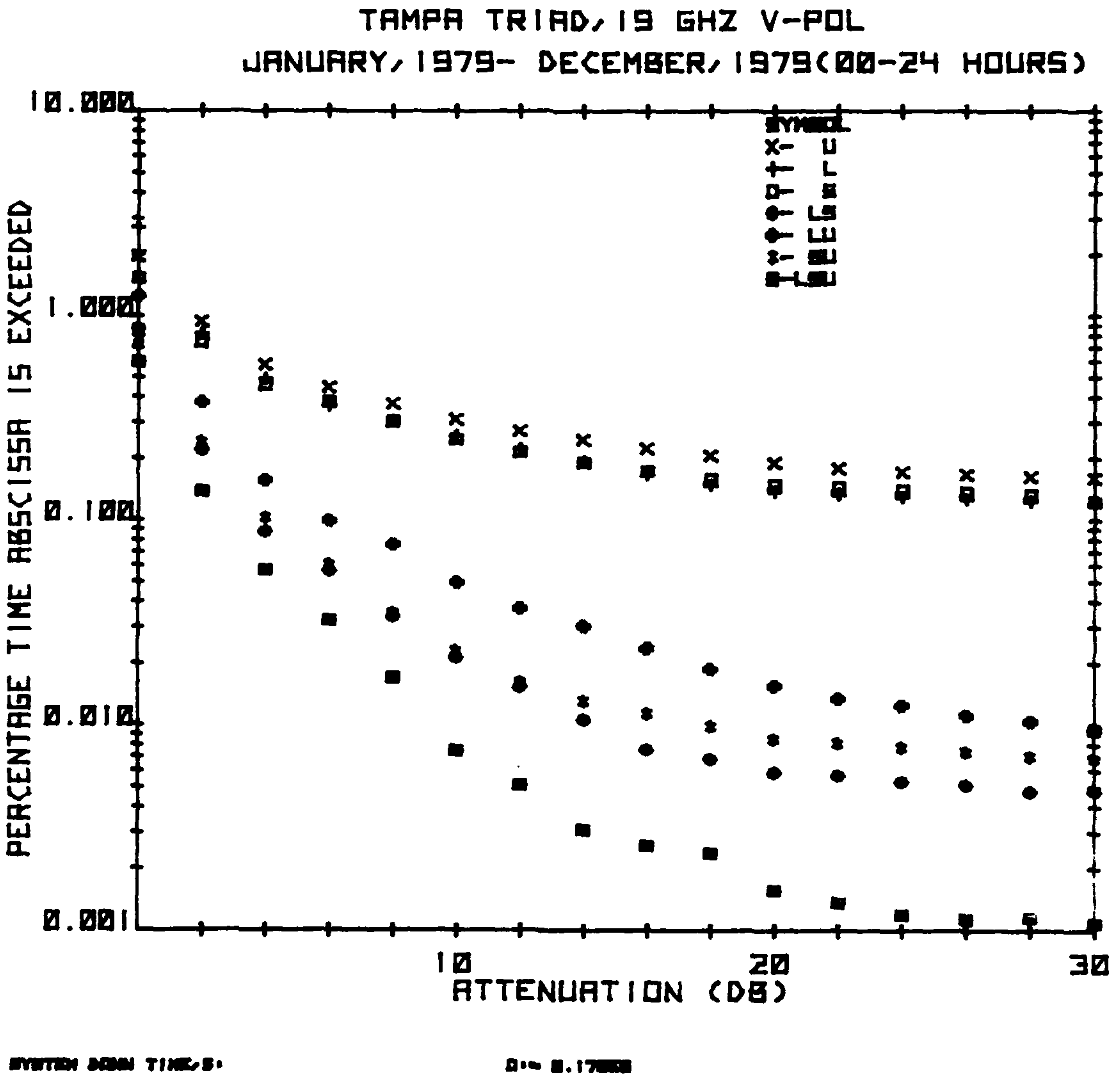


Figure 2-1. 19-GHz Attenuation Distributions, Tampa Triad, 1979

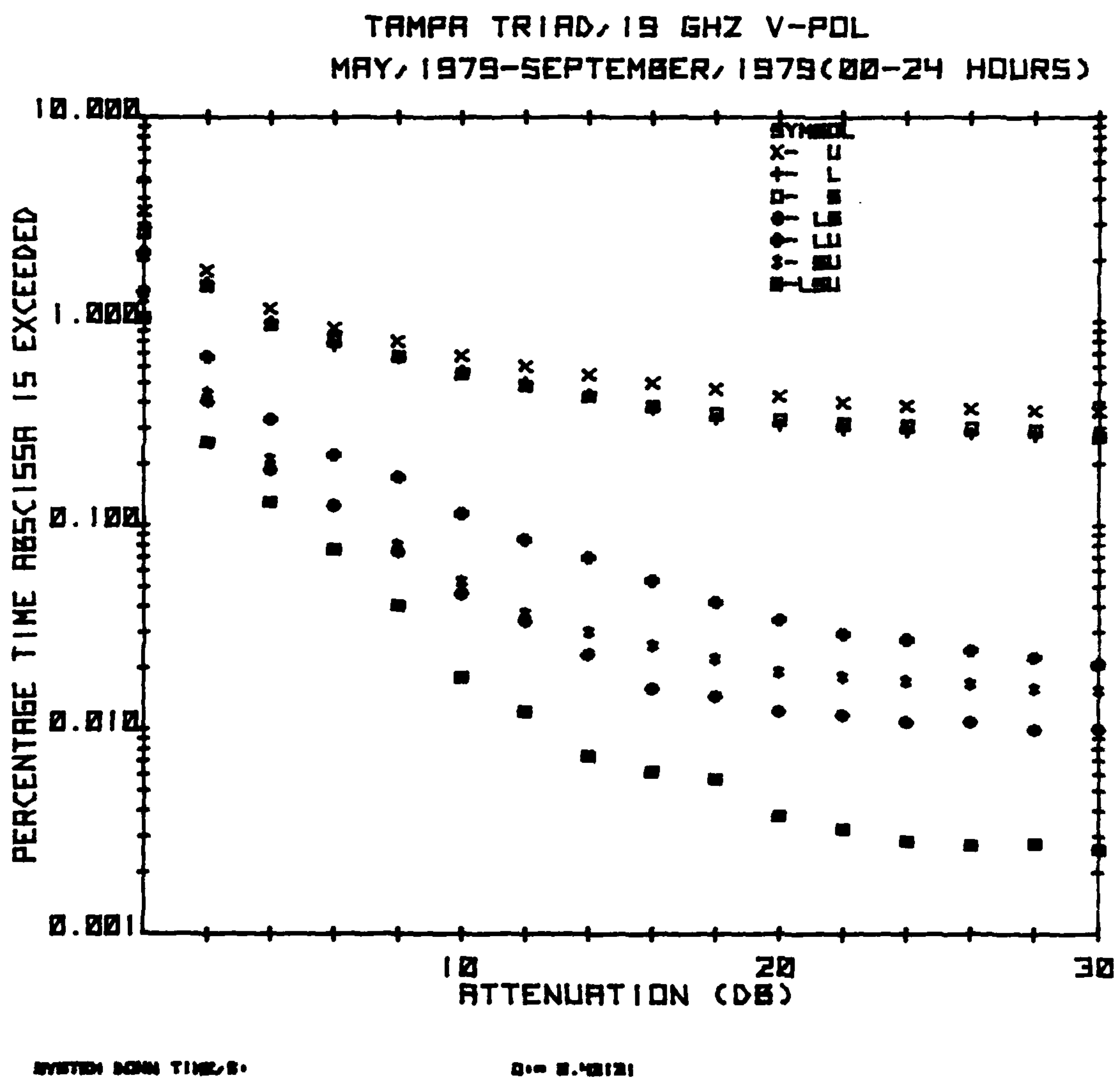


Figure 2-2. 19-GHz Attenuation Distributions, Tampa Triad, May-Sept 1979

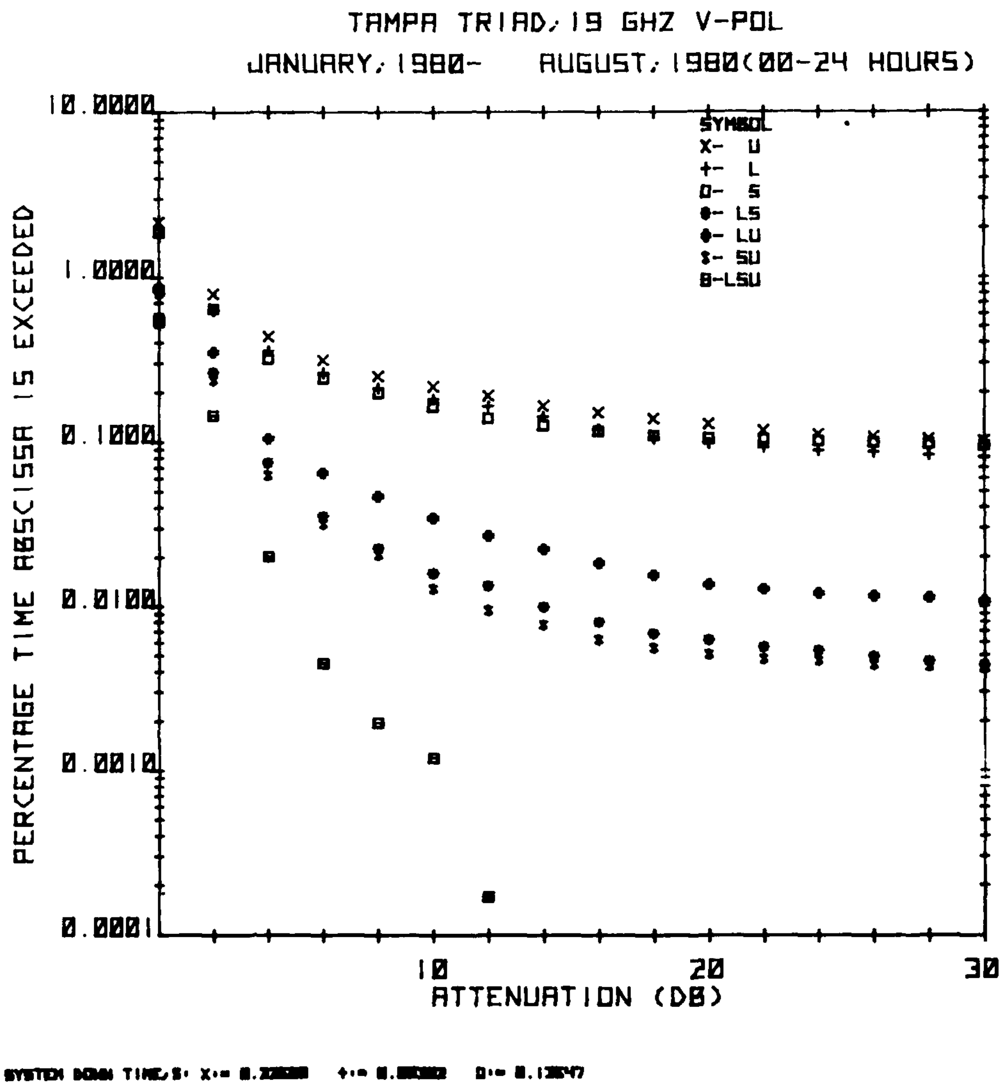


Figure 2-3. 19-GHz Attenuation Distributions, Tampa Triad, Jan-Aug 1980

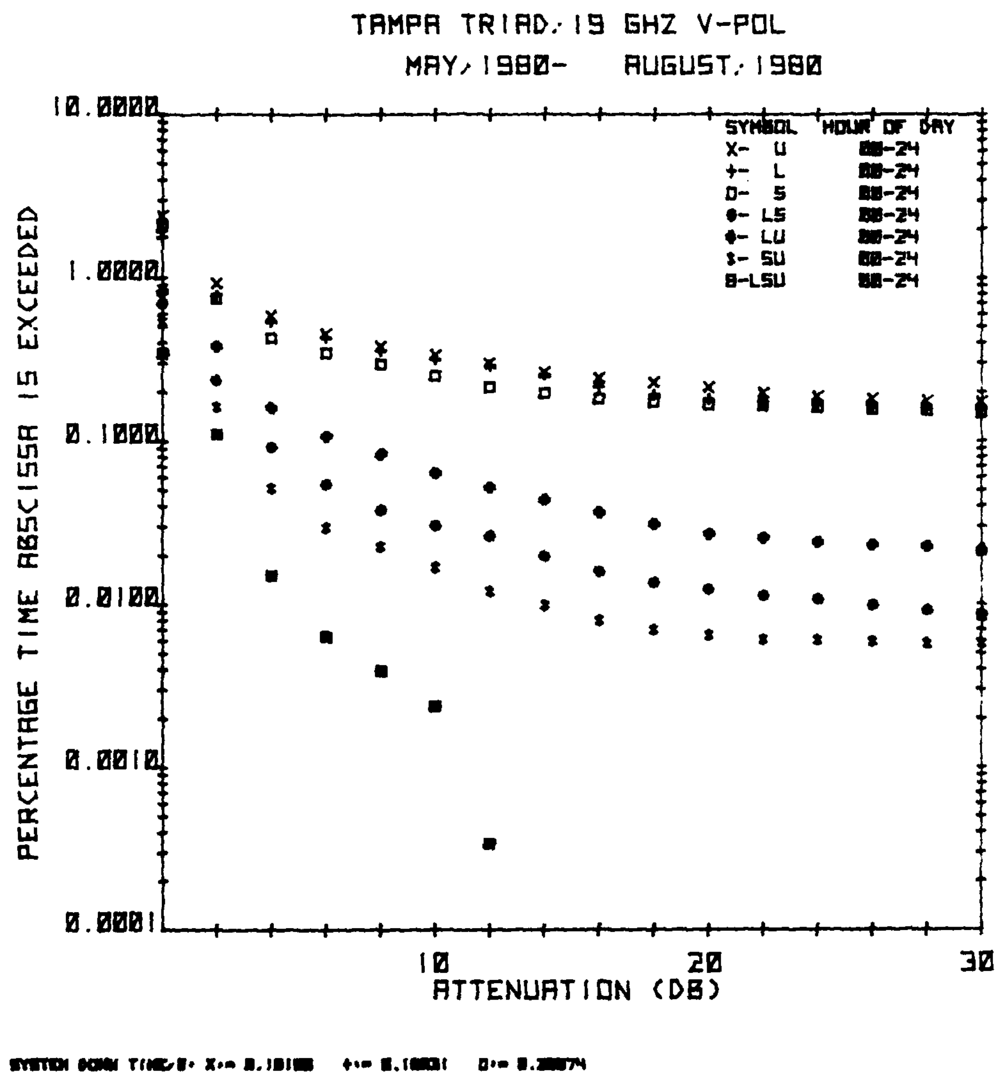


Figure 2-4. 19-GHz Attenuation Distributions, Tampa Triad, May-Aug 1980

As suggested above, the monthly distributions reveal that within a given month sites can differ significantly, and this is also true of pair diversity behavior. Here, in Tables 2-1 and 2-2 are tabulated the respective outage times at the 10-dB attenuation level, month by month. These tables should be compared with Tables 2-3 and 2-4 which give the rainfalls observed at the three sites and at Tampa International Airport, not far from Sweetwater.

For the individual summer months, U had the most outage in June and September; S in May and July; and L in August. Comparing L and S, June was very dry in both locations, with S being drier than L. So S had the least outage, only 0.05% in June. Rainfall at S was only 0.67 inch in June.

For the entire year 1979, excepting the two dry months of April and October, none of the single-site distributions met an objective that would correspond to an annual outage objective of 0.01%/10-dB, with the possible exception of S in November and U in December, when the objective was barely met.

With respect to diversity improvement, the longest pair, LS, had best propagation reliability every month excepting January, February, August and September when the pair SU had the better score of the two. LU is consistently the worst pair, and this has been true since inception of diversity recordings in 1978.

Even with three-site diversity, top performance as characterized by an outage of no more than 0.01% (at the 10-dB level) occurred in only two of the five consecutive rainy months. The considerable difference between sites as to total monthly rainfall is evident in Tables 2-3 and 2-4.

In contrast to most winter-month distributions (see Figure 2-6), each of the monthly distributions for the five rainy months has a flattish tail, which is produced by the rapid fade-in and fade-out character of both the observed rain attenuation and the observed rain rate. Figure 2-5 shows an analog recording for a typical summer rain event; notice that in this figure the steep sides of the attenuation plot are almost replicated in the slopes of the rain rate recording. The high rate of change of attenuation raises questions whether there will be adequate time to switch in power management schemes of various kinds designed to allocate more margin to rain-affected stations by a central control station. (See, for example, a proposed beam switching system with a pool of TDMA time slots for rain-affected stations, Acampora (1979).

TABLE 2-1

PERCENTAGE TIME, BY MONTH, FOR WHICH
10-dB ATTENUATION WAS EXCEEDED
TAMPA TRIAD, 1979

	USF	SWTR	LUTZ	LU	SU	LS	LSU
JAN	0.061	0.036	0.065	*	*	0.007	*
FEB	0.206	0.131	0.097	0.025	0.010	0.020	*
MAR	0.005	0.005	0.047	*	*	*	*
APR	*	*	0.002	*	*	*	*
MAY	0.726	0.809	0.791	0.217	0.139	0.101	0.061
JUN	0.370	0.500	0.185	0.030	*	*	*
JUL	0.390	0.513	0.307	0.029	0.083	0.025	0.0[illegible]5
AUG	0.784	0.715	0.874	0.137	0.029	0.065	0.013
SEP	1.155	0.685	0.683	0.157	0.012	0.039	0.011
OCT	*	*	*	*	*	*	*
NOV	0.051	0.009	0.042	*	*	*	*
DEC	0.010	0.024	*	*	*	*	*

* = 0%

TABLE 2-2

PERCENTAGE TIME, BY MONTH, FOR WHICH
10-dB ATTENUATION WAS EXCEEDED
TAMPA TRIAD, JAN-AUG 1980

	USF	SWTR	LUTZ	LU	SU	LS	LSU
JAN	0.105	0.051	0.015	*	*	*	*
FEB	0.009	0.049	0.033	0.002	*	0.003	*
MAR	0.141	0.097	0.059	0.015	0.030	0.003	*
APR	0.131	0.106	0.083	0.003	0.005	*	*
MAY	0.262	0.128	0.285	0.075	0.005	0.012	0.005
JUN	0.287	0.173	0.255	0.017	0.008	0.021	*
JUL	0.484	0.423	0.502	0.101	0.012	0.036	*
AUG	0.316	0.280	0.224	0.061	0.042	0.053	*

Note: Beacon terminated, Aug 31, 1980

* = 0%

TABLE 2-3

TOTAL MONTHLY RAINFALL IN INCHES, 1979
(MEASURED BY TIPPING-BUCKET RAIN GAUGE)

	USF	SWTR	LUTZ	TAMPA AIRPORT
JAN	N/A	N/A	N/A	5.72
FEB	2.88	N/A	N/A	2.87
MAR	4.08	N/A	N/A	2.43
APR	0.59	N/A	N/A	0.53
MAY	16.78	15.67	N/A	17.64
JUN	4.8	0.67	1.24	2.07
JUL	5.16	8.72	6.84	5.93
AUG	11.93	18.77	18.75	12.76
SEP	16.42	13.77	16.96	13.98
OCT	0.00	0.00	0.00	0.00
NOV	1.16	1.19	2.92	0.83
DEC	1.53	2.04	1.53	1.52

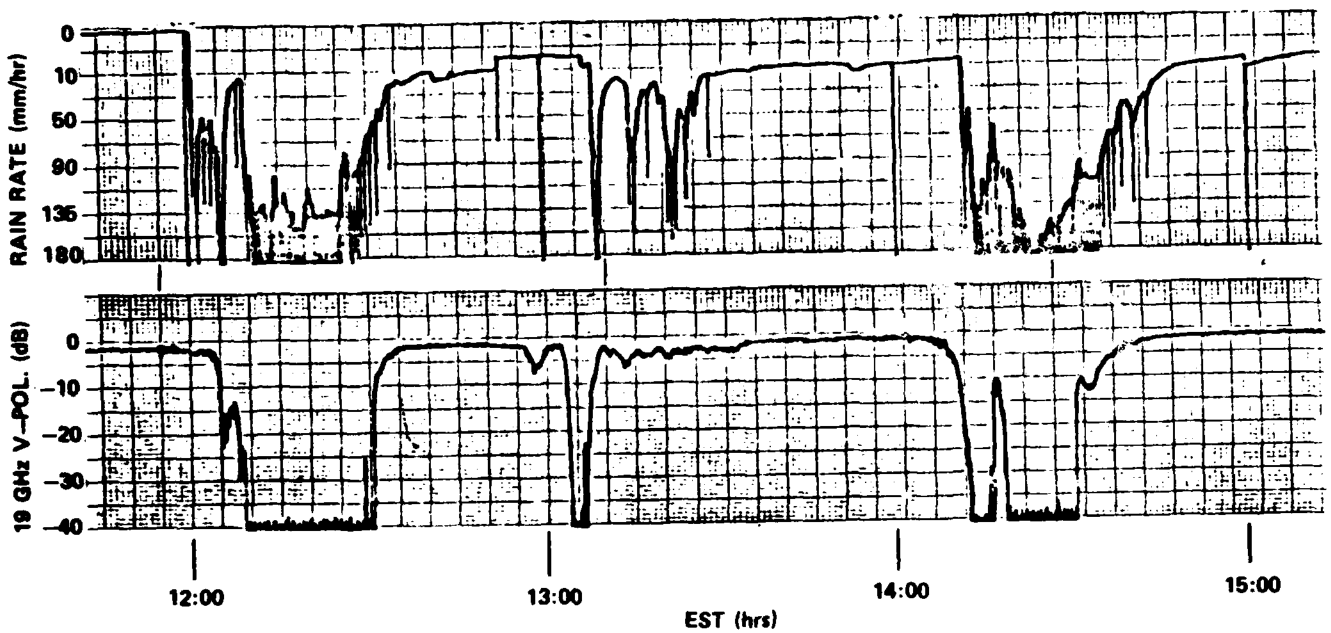
N/A = Not Available

TABLE 2-4

TOTAL MONTHLY RAINFALL IN INCHES, 1980, TAMPA

	USF	SWTR	LUTZ	TAMPA AIRPORT
JAN	3.05	3.06	1.95	1.70
FEB	1.76	2.08	1.09	2.00
MAR	3.46	4.87	3.52	3.10
APR	3.95	4.92	1.06	4.40
MAY	4.02	3.85	N/A	3.90
JUN	1.52	3.60	N/A	3.80
JUL	5.90	6.91	N/A	5.70
AUG	6.43	6.21	N/A	7.60
SEP	3.90	5.12	N/A	4.10
OCT	0.53	0.83	0.83	1.30
NOV	3.25	2.15	4.17	2.70
DEC	0.59	0.54	0.72	0.40

EVENT RECORDING AT USF, SEPTEMBER 13, 1979



THE UPPER RECORD IS PRODUCED BY A RAIN-RATE GAUGE (CURVE ENVELOPE) WHILE A TIPPING-BASKET GAUGE IS RESPONSIBLE FOR THE HALF–SIZE DOWNWARD TICK MARKS. THE FULL-SIZE MARKS ARE HOUR MARKS.

Figure 2-5. Rainfall and 19-GHz Attenuation Recordings at USF, Sept. 13, 1979

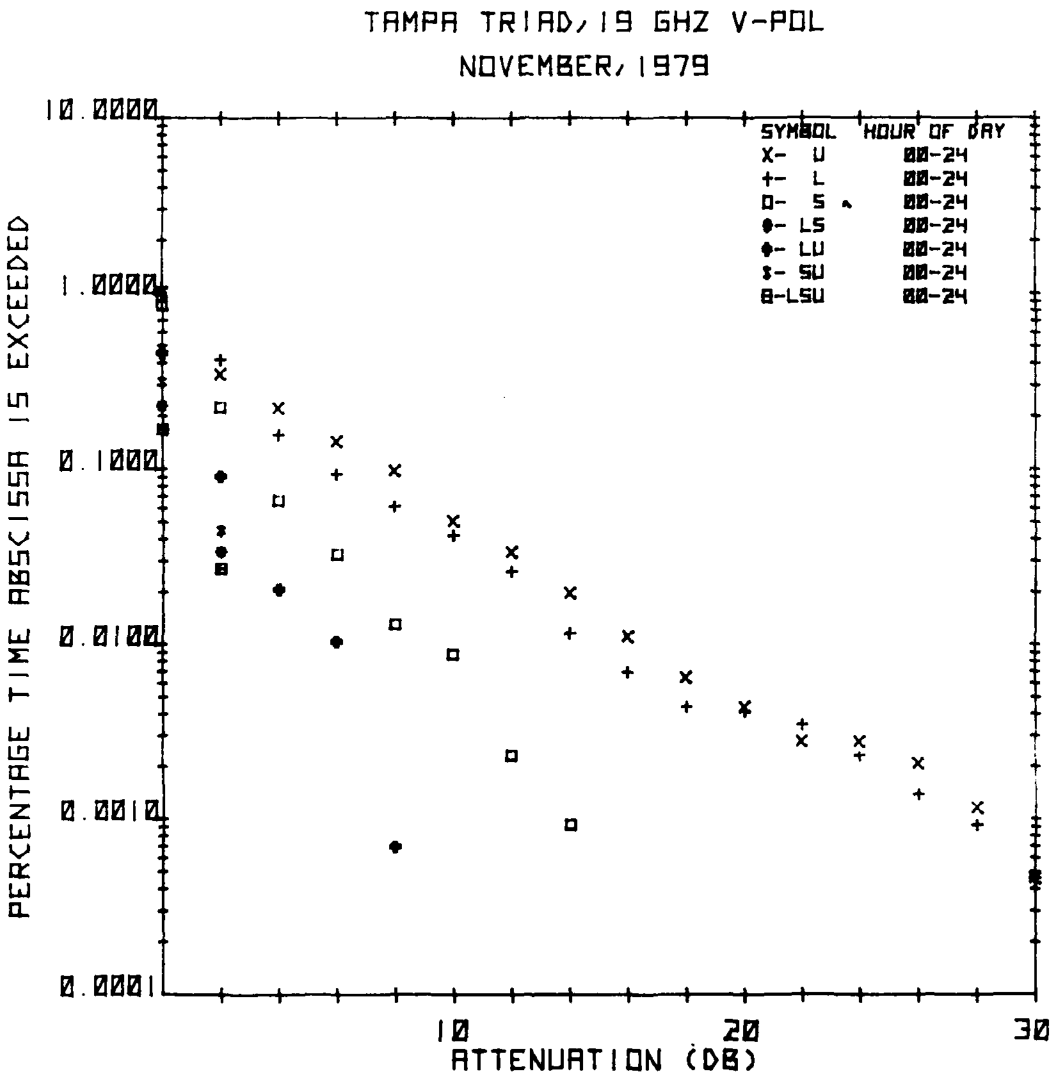


Figure 2-6. 19-GHz Attenuation Distributions, Tampa Triad November 1979

Comparison of Figures 2-1 and 2-2 leads to the approximate relation $P_{yr} = 0.5\ P_{sum}$ where P_{sum}, P_{yr} are the outage percentage for summer 1979 and for the entire year, respectively. Had rain events been confined to the five summer months, the ratio of P_{yr}/P_{sum} would be equal to 5/12. The actual measured ratio of 0.5 indicates that about 80% of all rain-induced attenuation occurred during the five summer months of 1979.

SECTION 3
19 AND 29 GHz ATTENUATION DISTRIBUTIONS FOR TAMPA AND WALTHAM

3.1 WALTHAM AND TAMPA DATA FOR 1979

Figures 3-1 and 3-2 show the 1979 19 and 29 GHz distributions for Tampa (USF) and Waltham respectively.

Though the total 1979 annual rainfall in Tampa was only slightly greater than 1.5 times that in Waltham (1676 mm versus 1041 mm) rain rates were almost always higher in Tampa. The result is that for attenuation of about 10-db, the outage percentage at Tampa is about 8-10 times that at Waltham, for the year.

Table 3-1 gives the percentage outages at the 10-dB level month-by-month for Tampa and Waltham, for both frequencies. With the exception of January, April and October, notable dry months in Tampa, the outage percentages in Tampa exceed those in Waltham, and especially during the summer months, Tampa's rainy season.

Table 3-2 lists the attenuation ratio (29 GHz divided by 19 GHz) as a function of the 19-GHz attenuation, taken from the distributions in Figures 3-1 and 3-2. The Waltham ratios tend to be higher than the Tampa ones for 19 GHz attenuation of 6-12 dB. The Tampa ratios tend to decrease slightly with higher 19 GHz attenuation, which is the trend predicted by transmission theory. (A mean value of 1.94 was found by Bell Laboratories in their COMSTAR beacon measurements at Palmetto, Georgia.) It should be emphasized that the ratios given here are statistical in nature. In any one rain event or in any one month, the ratio may have much wider range of value, as was shown in our 1978 report (TR 79-471.4). The ratio predicted by Oguchi and Hosoya (1973) tends towards 2 at high rain rates; Laws-Parson drop-size distribution was assumed. A significantly different drop-size distribution would lead to a different ratio.

3.2 COMPARISON WITH ATTENUATION PREDICTION MODELS

In an improved version of his global rain prediction model, Crane (1980) formulates the attenuation/rain-rate relationship as:

$$A = \alpha R^{\beta} \cdot L(R, D, \beta)$$

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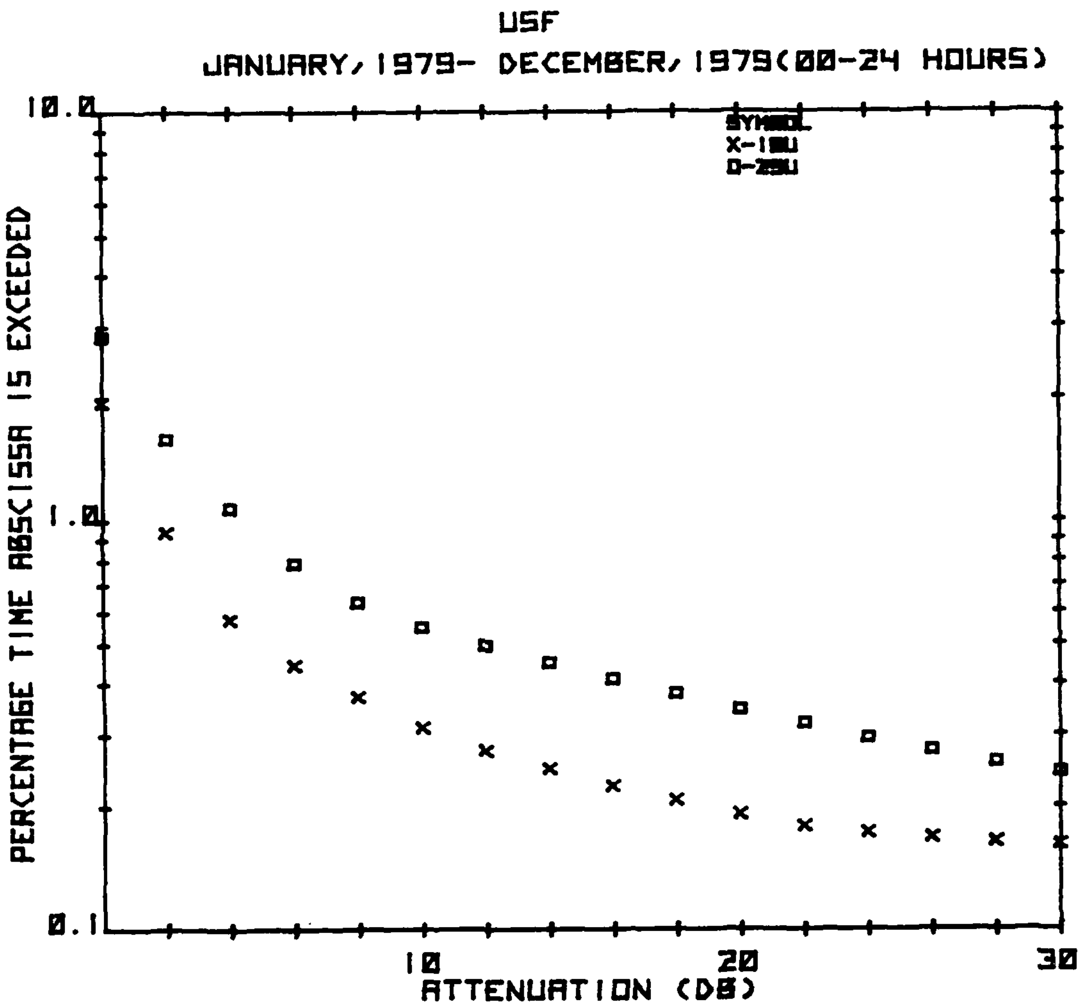


Figure 3-1. 19/29 GHz Attenuation Distributions, USF, 1979

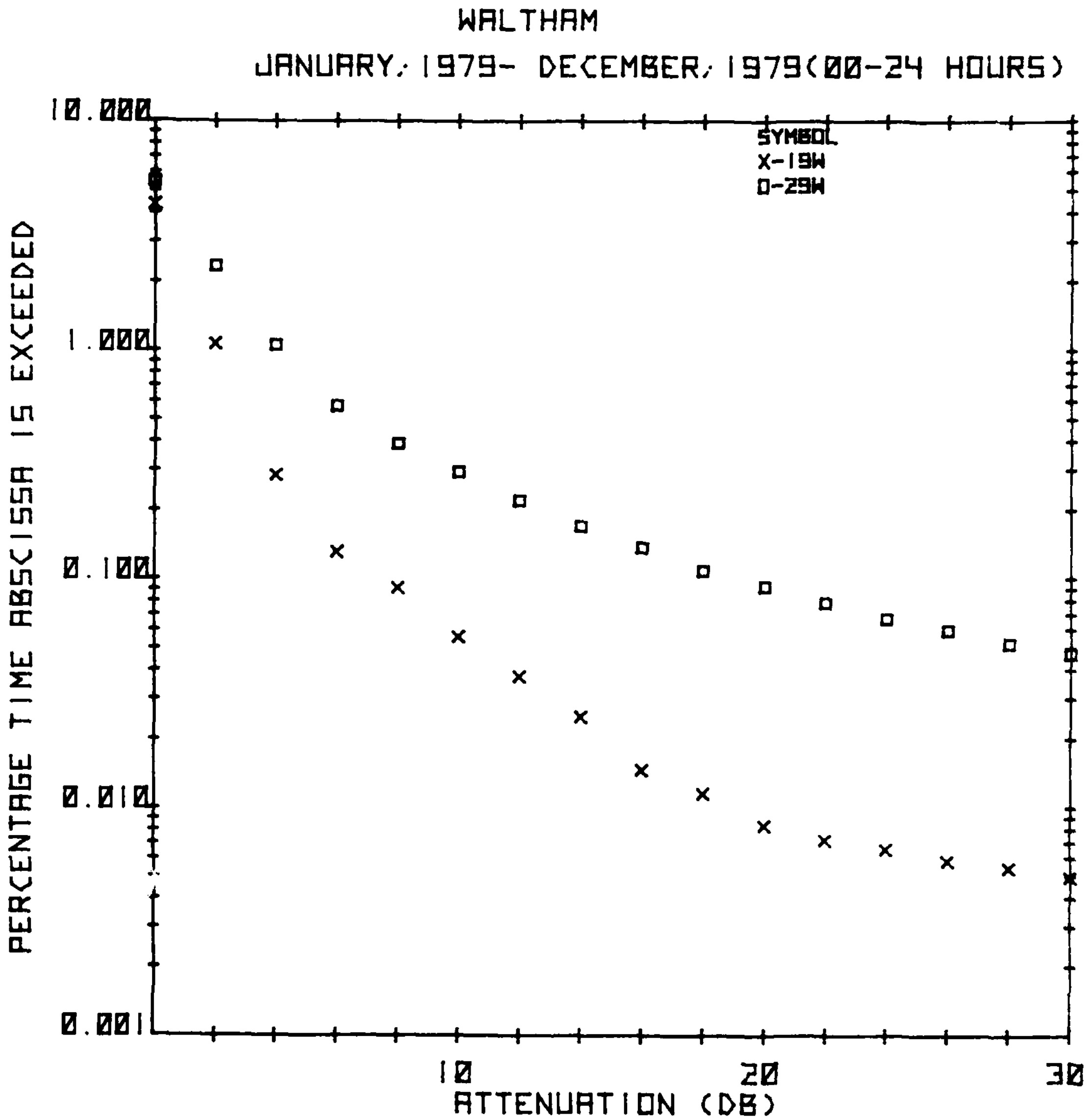


Figure 3-2. 19/29 GHz Attenuation Distributions, Waltham, 1979

where αR^{β} is the specific attenuation rate, such that $\alpha = \alpha(f)$, $\beta = \beta(f)$ alone, since they involve rain-drop distributions; L is an effective path length, with the distance D never exceeding 22.5 km. L is described by a piecewise exponential expression. D is the surface projection of the slant range rainy section of the path to the satellite.

A prior (1978) Crane model utilized the power law $L = \gamma R^{-\delta}$, such that $\gamma = \gamma(D)$, $\delta = \delta(D)$. In the newer model there is some very weak frequency dependence contained in L via the β parameter. Under the older model, the ratios of attenuations, 29 GHz to 19 GHz, for the antenna and path would, at least to zero order, eliminate any L dependence so that

$$A_{29}/A_{19} = (\alpha_{29}/\alpha_{19})\ R^{\beta_{29}-\beta_{19}} = cR^{d}$$

Using Crane's chosen tabulation for α, β, we find c = 2.46 and d = -0.0138.

Applying Crane's newer model to the Tampa geometry for D-3 (87° W) and rain rates that give 19 GHz attenuations between 2 and 16 dB, the attenuation ratio starts at about 2.38, decreasing to 2.30; these values are about 5% higher than the observations listed in Table 3-2.

TABLE 3-1

PERCENTAGE TIME ATTENUATION EXCEEDED 10-dB
TAMPA AND WALTHAM
19 AND 29 GHz

	19W	19U	29W	29U	19W	19U	29W	29U
JAN	0.222	0.061	0.585	0.513	0.000	0.105	0.033	0.201
FEB	0.000	0.206	0.002	0.367	0.000	0.009	0.000	0.058
MAR	0.000	0.005	0.000	0.040	0.000	0.141	0.027	0.334
APR	0.002	0.000	0.051	0.007	0.000	0.131	0.354	0.244
MAY	0.015	0.726	0.196	1.48	0.020	0.262	0.166	0.432
JUN	0.021	0.370	0.197	0.509	0.126	0.287	Beacon Off	Beacon Off
JUL	0.122	0.390	0.479	0.686	0.269	0.484	Beacon Off	Beacon Off
AUG	0.144	0.794	1.048	1.49	0.054	0.316	0.336	0.439
SEP	0.055	1.155	0.472	1.84				
OCT	0.058	0.000	0.238	0.001				
NOV	0.020	0.051	0.186	0.168				
DEC	0.000	0.01	0.022	0.101				

TABLE 3-2

ATTENUATION RATIO, 29 GHz VS. 19 GHz, FOR TAMPA AND WALTHAM
BASED ON THE 1979 YEARLY DISTRIBUTIONS

19 GHz ATTENUATION OBSERVED	TAMPA (USF) RATIO	WALTHAM RATIO
2 dB	2.4	2.0
4	2.25	2.25
6	2.25	2.7
8	2.25	2.5
10	2.2	2.7
12	2.17	2.5

SECTION 4
WORST-MONTH STATISTICS

In applying the results of rain attenuation measurements to the design of systems, it is desirable to know the path performance during a "worst month", as defined for example, by CCIR recommendation 522 [CCIR, Kyoto, 1978] where worst month is taken to mean "median worst month" for all the months for which statistics are available. It is also valuable to use the distribution of attenuation (or rain rate) for the worst month as a basis for estimating the yearly distribution that would apply if measurements could have been continued over a number of years. This involves the application of some extremal statistics, and has been set forth in the literature. [Crane and deBrunner (1978); Brussard and Watson (1978); CCIR Draft Report 723 (1980)]

In this section we shall focus on the ratio of the exceedance in a worst month to that in the yearly distribution for 1979 only. When an average yearly distribution is prepared from the many-year statistics of the Tampa Triad, a more exact ratio will be obtained in the sense desired by the CCIR.

As the referenced papers show, if the worst month were a solitary month then the ratio ought to be around 12, but when rainfall is seasonal over several months that are nearly the same, then the ratio falls to a value of about half the above ratio or even less. (See particularly the paper by Brussaard and Watson (1978)).

Figure 4-1 identifies the worst months from the Tampa single-site distributions, and it can be seen that the ratio lies between 3 and 4.

For S the worst month was May 1979, while for U it was September. For L, either one or two months could be chosen depending upon the attenuation level taken as objective: For attenuations below 15 dB, August was worst, while May was worst for higher attenuations.

Figure 4-2 shows the worst-month situation for the diversity combinations; the U curve for September is included for comparison. For LS and LU the ratio lies between 4 and 5, for SU it lies between 6 and 7, while for LSU, the three-site combination, the ratio lies between 6 and 12. For attenuations greater than 20 dB, the LSU combination achieves the desired factor of 12, indicating that for it there was only one "worst" month.

Figure 4-3 shows the worst-month situation for Waltham. Like L, Waltham has two months that can possibly qualify to be "worst": January and August. January 1979 was unusual with a great deal of widespread rain, with rain rates below 30 mm/hr, and it turned out to be the worst month with respect to attenuations below 15 dB. August involved many intense thunderstorms resulting in high rain rates, and so qualified for worst-month nomination for attenuation above 15 dB.

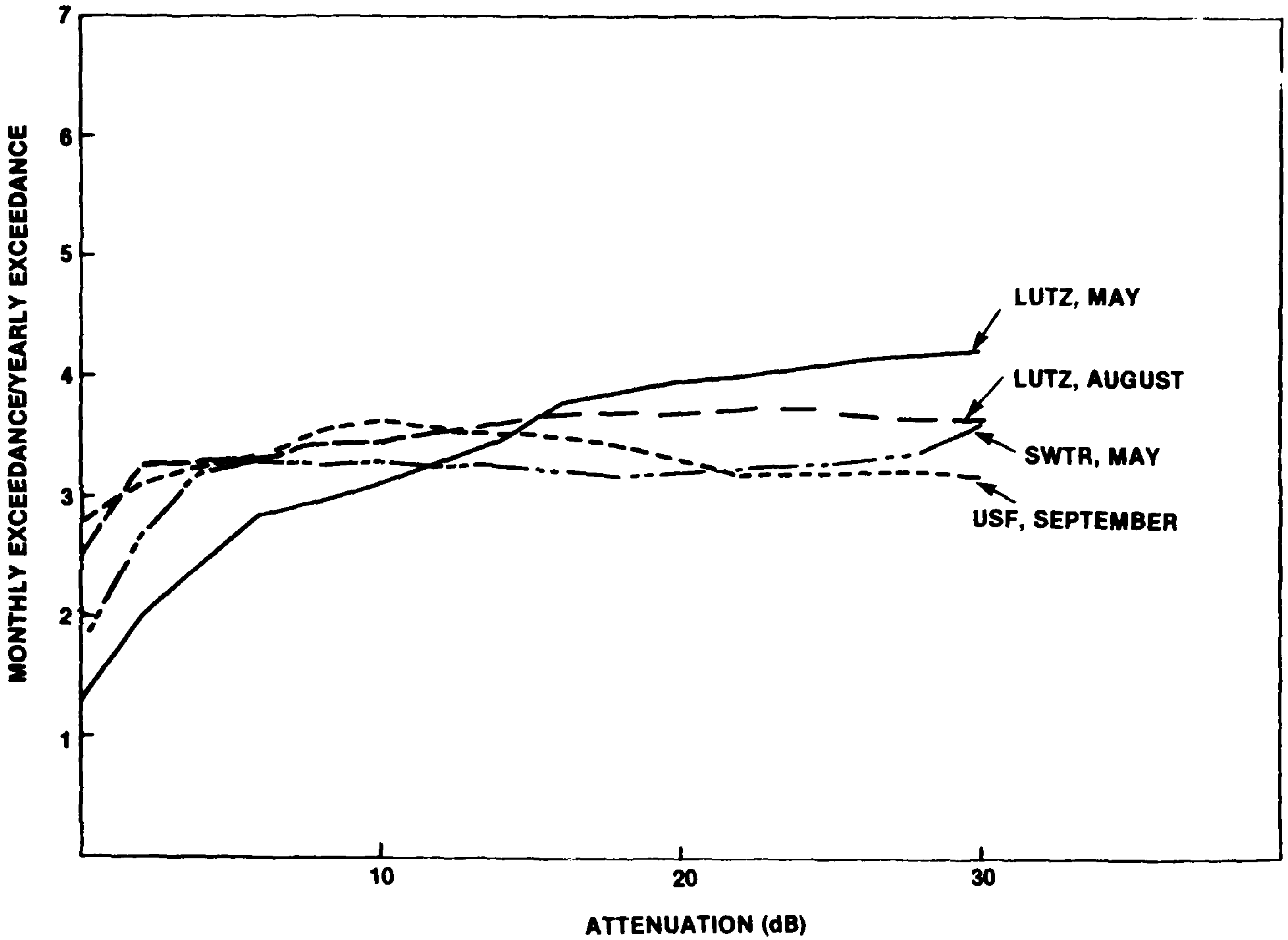


Figure 4-1. 1979 Worst Months for Single Sites, Tampa, Exceedance Ratios.

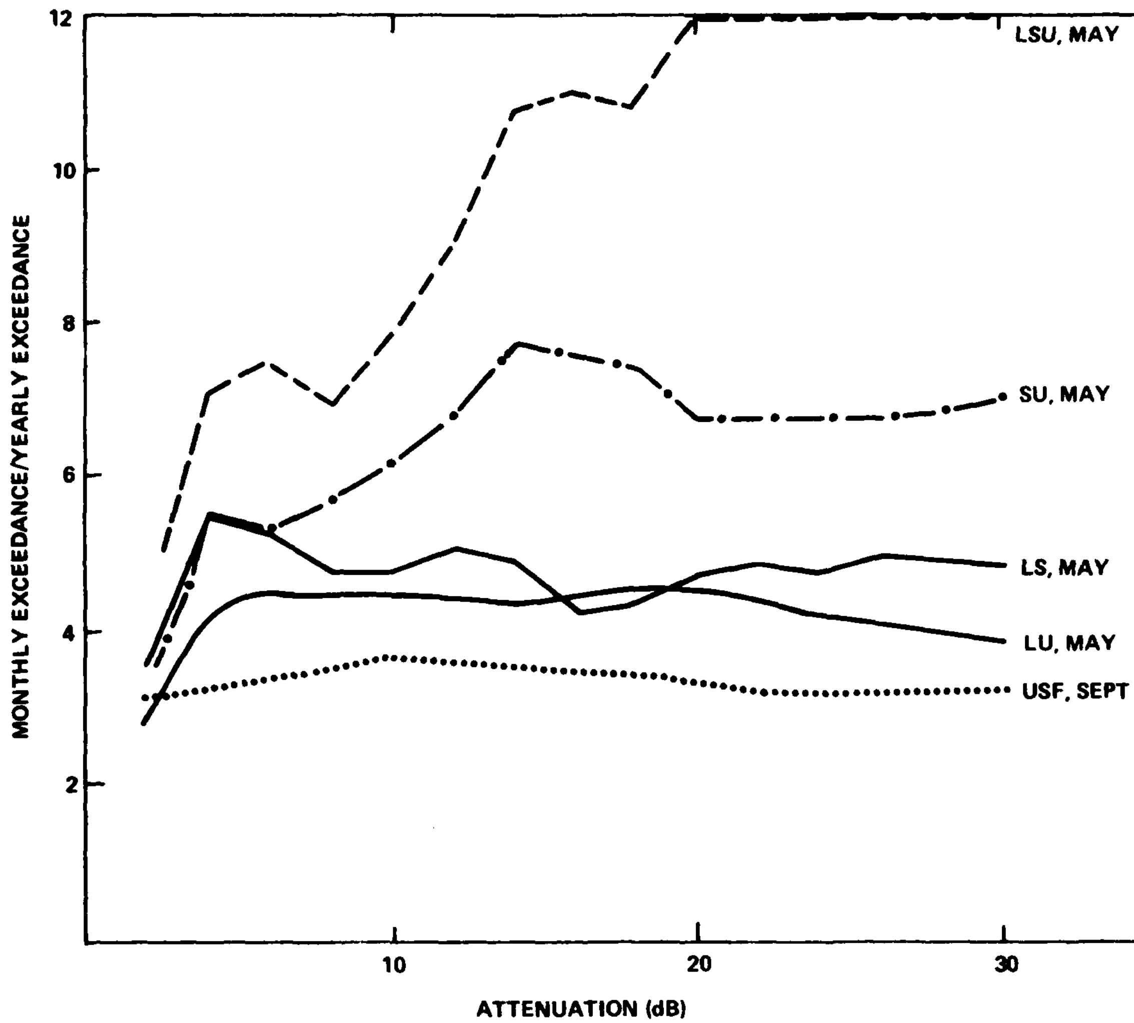


Figure 4-2. 1979 Worst Months for Combined Sites, Tampa. Exceedance Ratios.

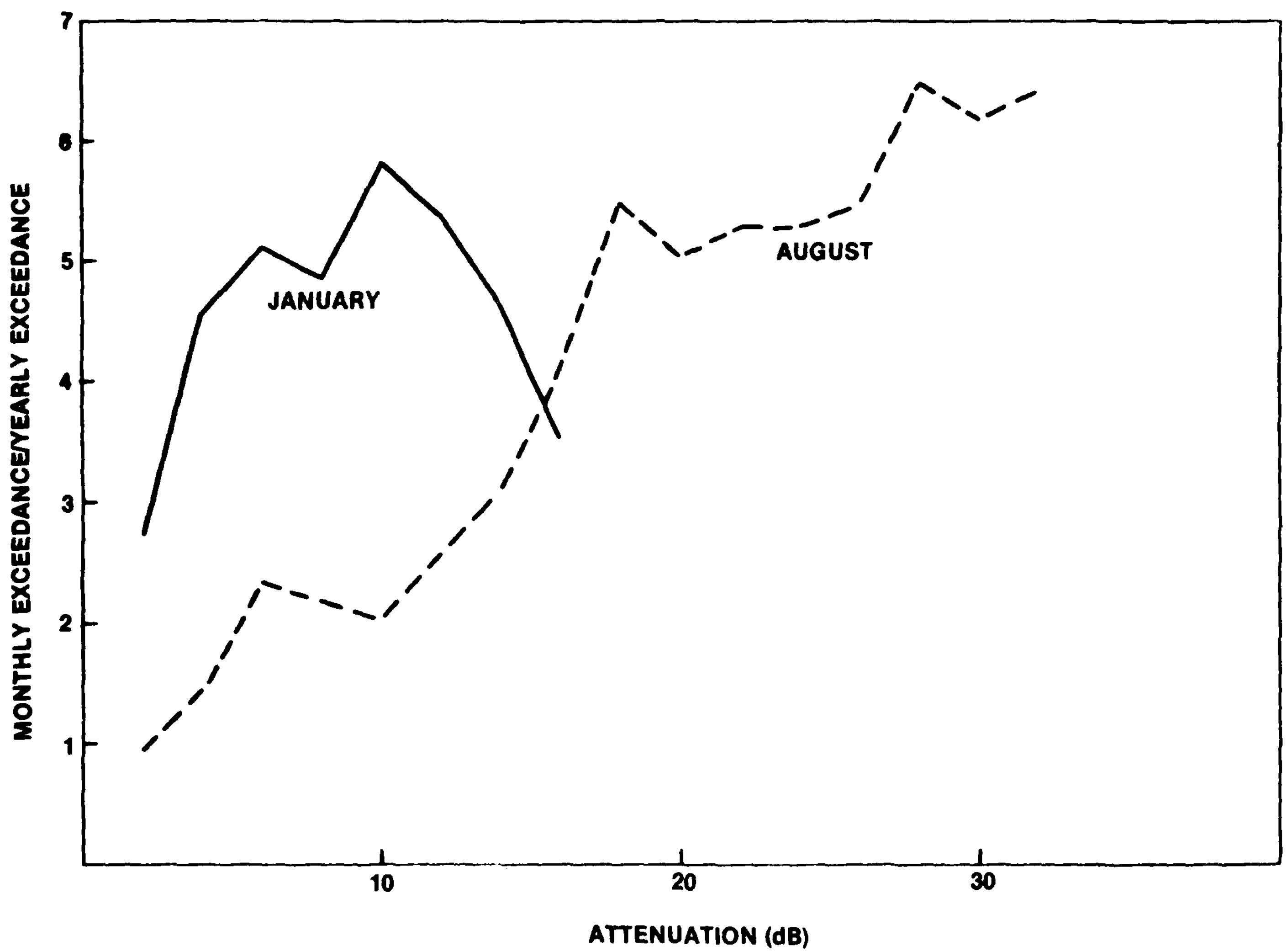


Figure 4-3. 1979 Worst Months for Waltham. Exceedance Ratios.

SECTION 5

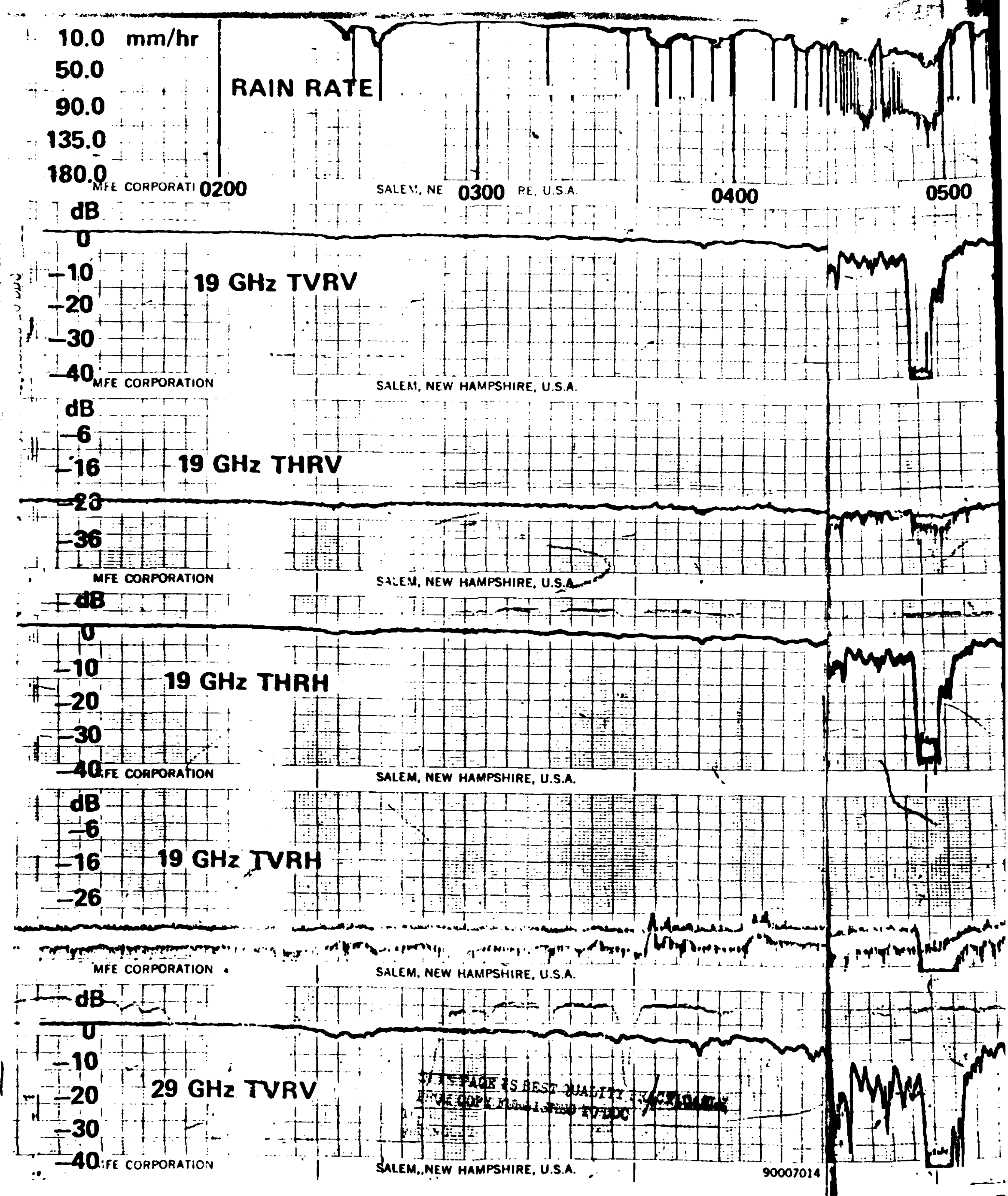
THE EXTRAORDINARY RAIN EVENT AT TAMPA ON MAY 8, 1979

On May 8, 1979 an unprecedented rain event occurred in the metropolitan area of Tampa, commencing at about 0200 h, continuing unabated until 1700 h. During these 15 hours, 13.32 in. (338 mm) rain accumulated at U, and 11 in. (279 mm) at S. (A rain-gauge malfunction prevented accurate reading at L). The official record at Tampa International Airport was 11.45 in. (290 mm) which is very close to the figure for S. There was considerable flooding, and some tornado-like activity, with much consequential property damage and some loss of life.

Figure 5-1 is a reproduction of the analog recording at U for this period. L and S recordings have similar behavior. At the 10-dB level, the outage times were: U, 194 min; S, 260 min; and L, 180 min. Considering diversity at the same attenuation level, the outage times fell significantly: LS, 42 min; LU, 94 min; and SU, 47 min. For the three-site combination, LSU, the net outage was 23 min. The superior performance of SU and LS over LU should be noted. Though LS is slightly better than SU, it does not mean on an a priori basis that the longest baseline should have the best performance. This "competition" between SU (16 km) and LS (20 km) has been noted also when tabulations of diversity improvement by month are examined.

Figure 5-2 contains the plots of outage times versus attenuation for the combinations just discussed.

On examining the analog records and concentrating on the times associated with complete drop-out of signal (> 28 dB), many two-site simultaneous drop-outs were noted. But for LSU, there was only one complete drop-out, lasting less than four minutes.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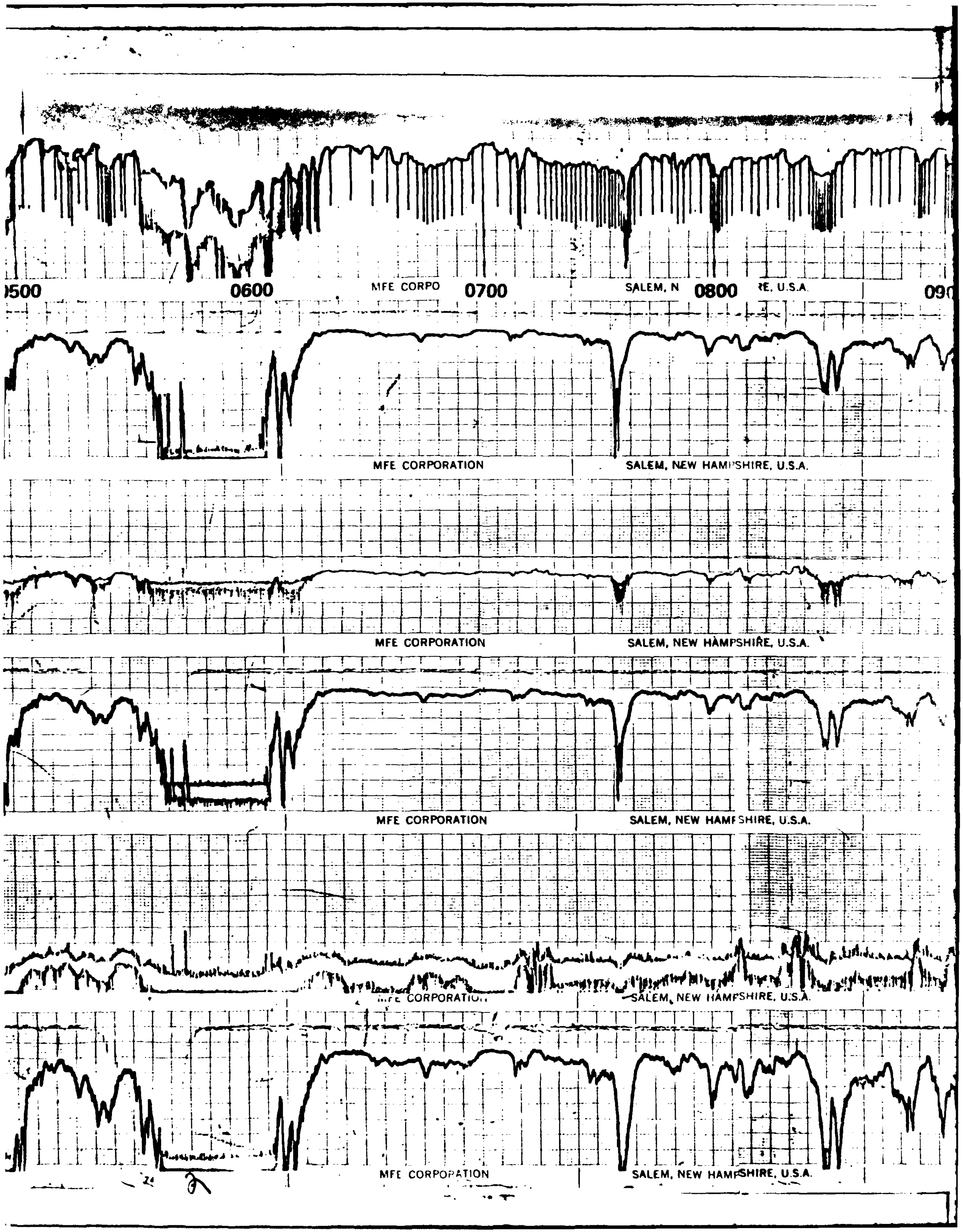

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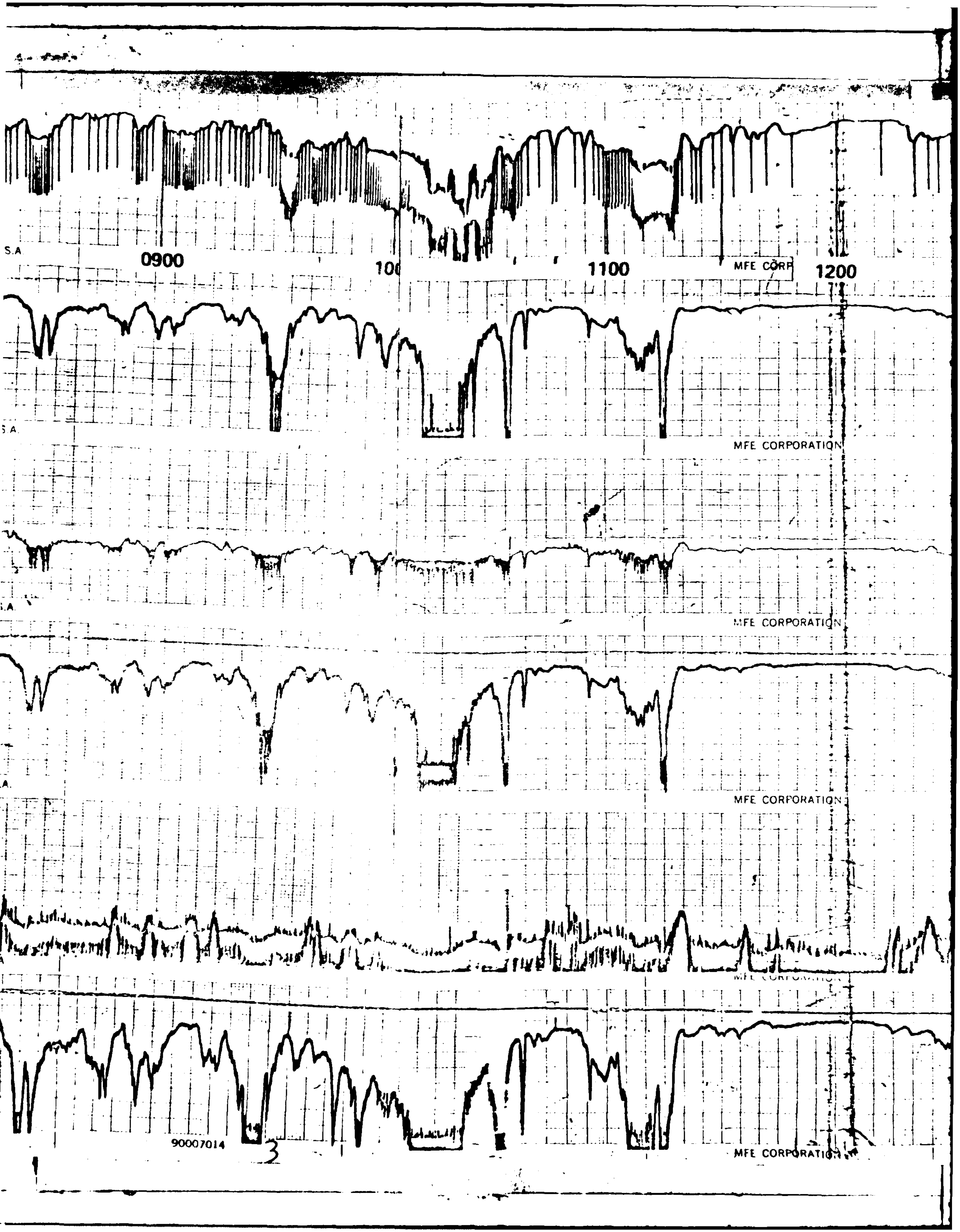
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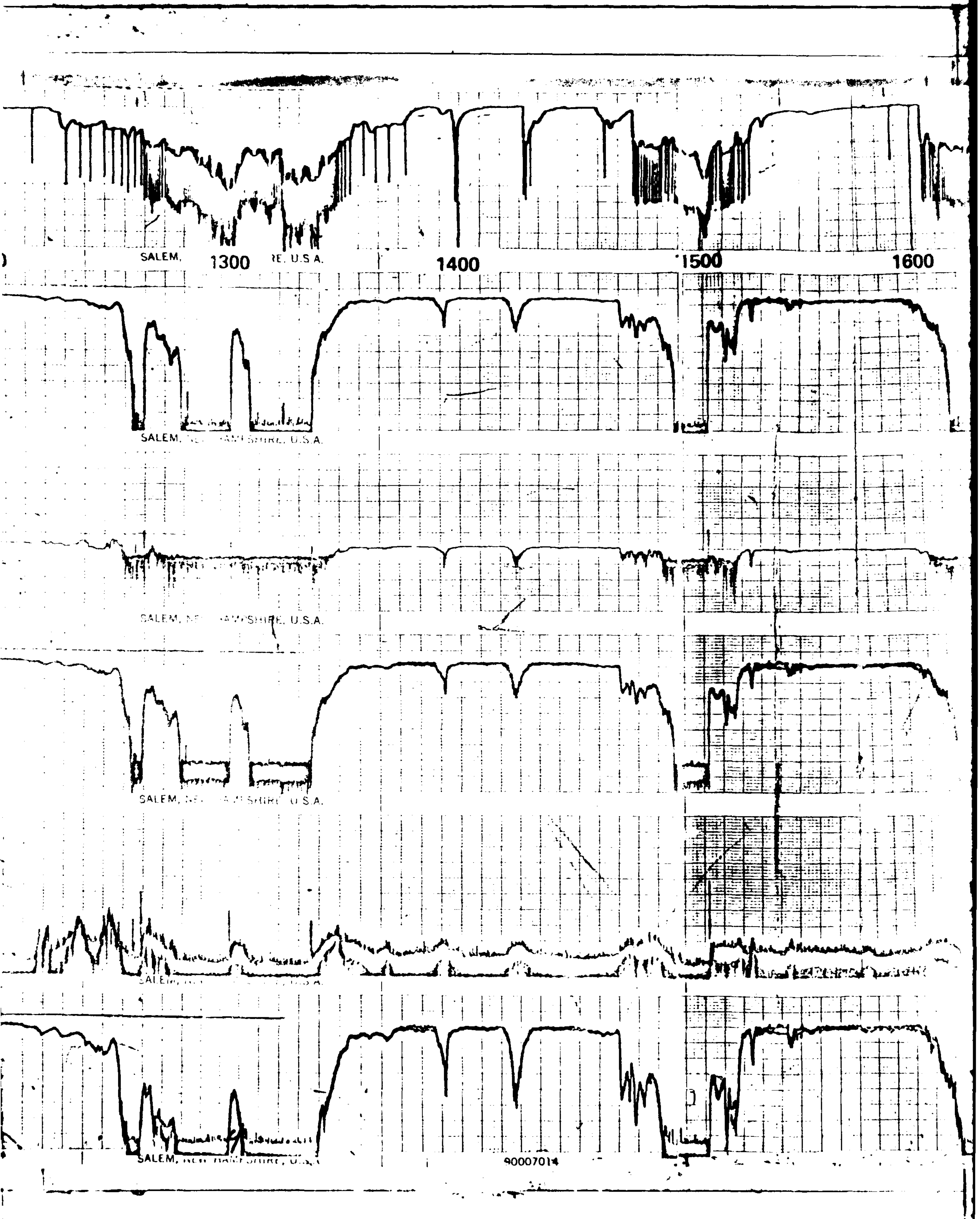
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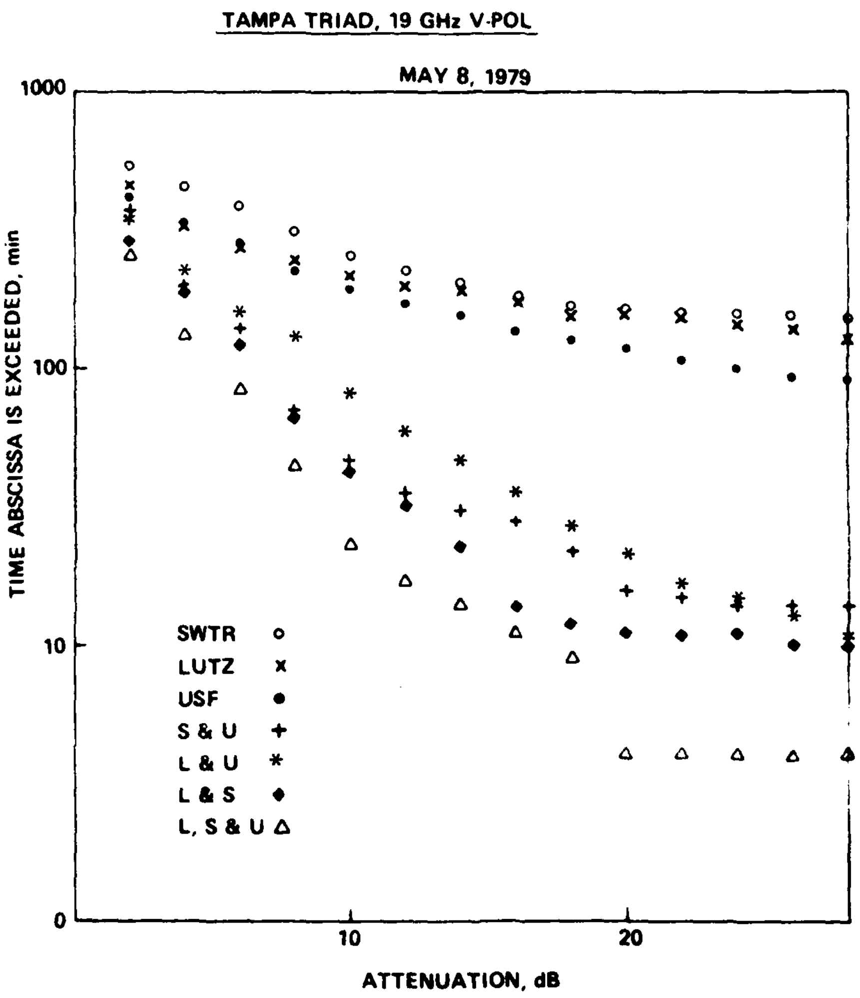

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Figure 5-2. Attenuation Exceedances, 19-GHz, Tampa Triad, May 8, 1979

SECTION 6

APPLICATION OF LOG-NORMAL DISTRIBUTIONS

Lin (1973) has shown that both rain-rate and rain attenuation distributions will tend to be describable by log-normal distributions, except for those parts of the distribution that are contributed by the rarest events. The actual relationship for attenuation is:

$$P(A > A_1.) = (P_o/2) \text{ erfc } [(\log(A_1./A_m))/S_A \sqrt{2}]$$

where

$P(A > A_1)$ = probability that A, the attenuation in dB, exceeds A_1 dB

A_m = attenuation corresponding to the median log A

S_A = standard deviation (of log attenuation)

P_o = fraction of time rain attenuation was non-zero

To use this distribution as a test fit, it is necessary to determine P_o, and having determined it, to plot the normalized result on log-normal probability paper. If a straight line fit is obtained, this allows the determination of A_m and S_A. Since determining P_o involves determining if there was some small attenuation at threshold, it is clear that an applicable value may not be that easy to obtain, for many small contributions to the attenuation are made by clouds, fog and the like, especially at these radio frequencies.

To exclude these effects, a 2-dB threshold is used. All attenuation events with less than 2 dB maximum attenuation were ignored. For attenuation events with more than 2-dB maximum attenuation, the total time that there is attenuation is recorded, and the total of this time in percent is used as P_o [Watson (1978) provisionally used a 3-dB threshold for 20 GHz.]

The results for Tampa are shown in Figures 6-1, 6-2 and 6-3. The first of these is for a typical summer month, the second for the set of five summer months in 1979, and the last is for the year's distribution.

Observation of the measured 19 GHz distribution indicates that each distribution can be fitted almost perfectly by two log-normal distributions with a common break point at 20-dB attenuation level. Only the log-normal fits for attenuation range up to 20 dB are shown in solid lines.

Results for Waltham for both 19 and 29 GHz are shown in Figures 6-4, 6-5 and 6-6. Figure 6-4 is for a typical summer month (June in this case), Figure 6-5 is for the entire summer, while Figure 6-6 is the year's distribution.

In Figures 6-7 and 6-8 are shown the log-normal fits for the 19 and 29 GHz attenuation distributions at U, the former for summer only, the latter for the entire year. Excellent fits appear in both cases.

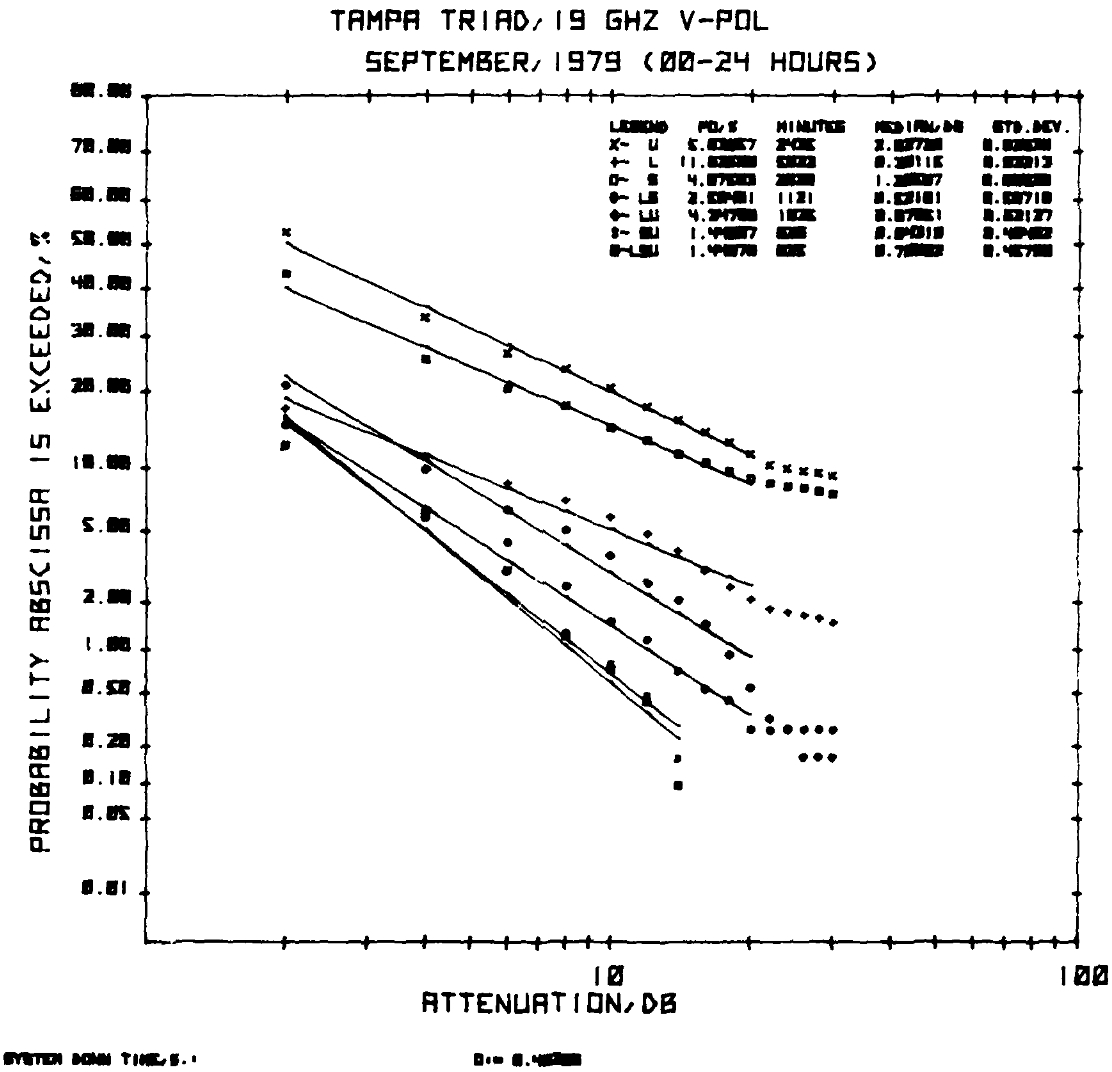

Figure 6-1. 19-GHz Lognormal Attenuation Plots, Tampa Triad, September 1979

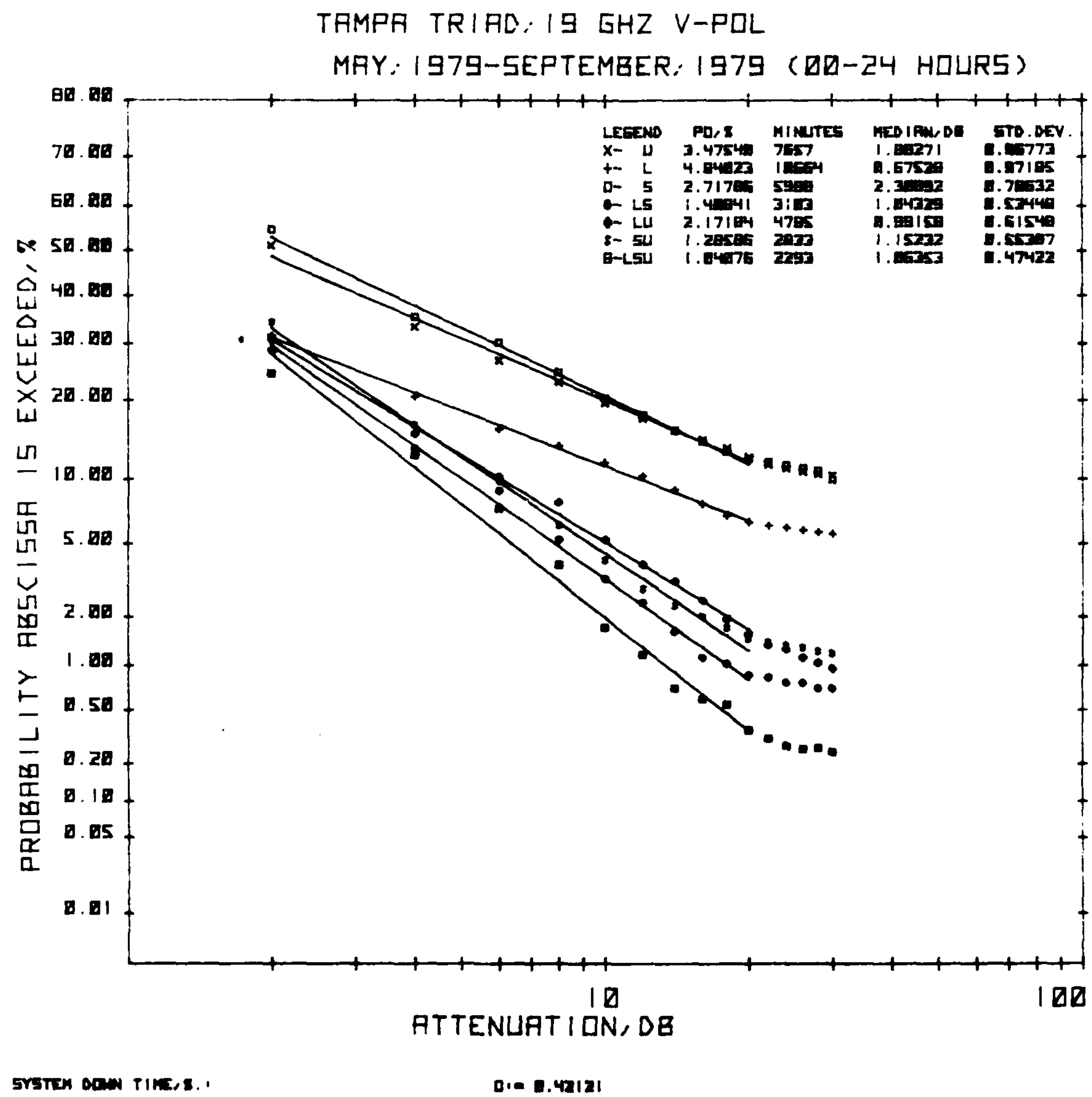

Figure 6-2. 19-GHz Lognormal Attenuation Plots, Tampa Triad, May-Sept 1979

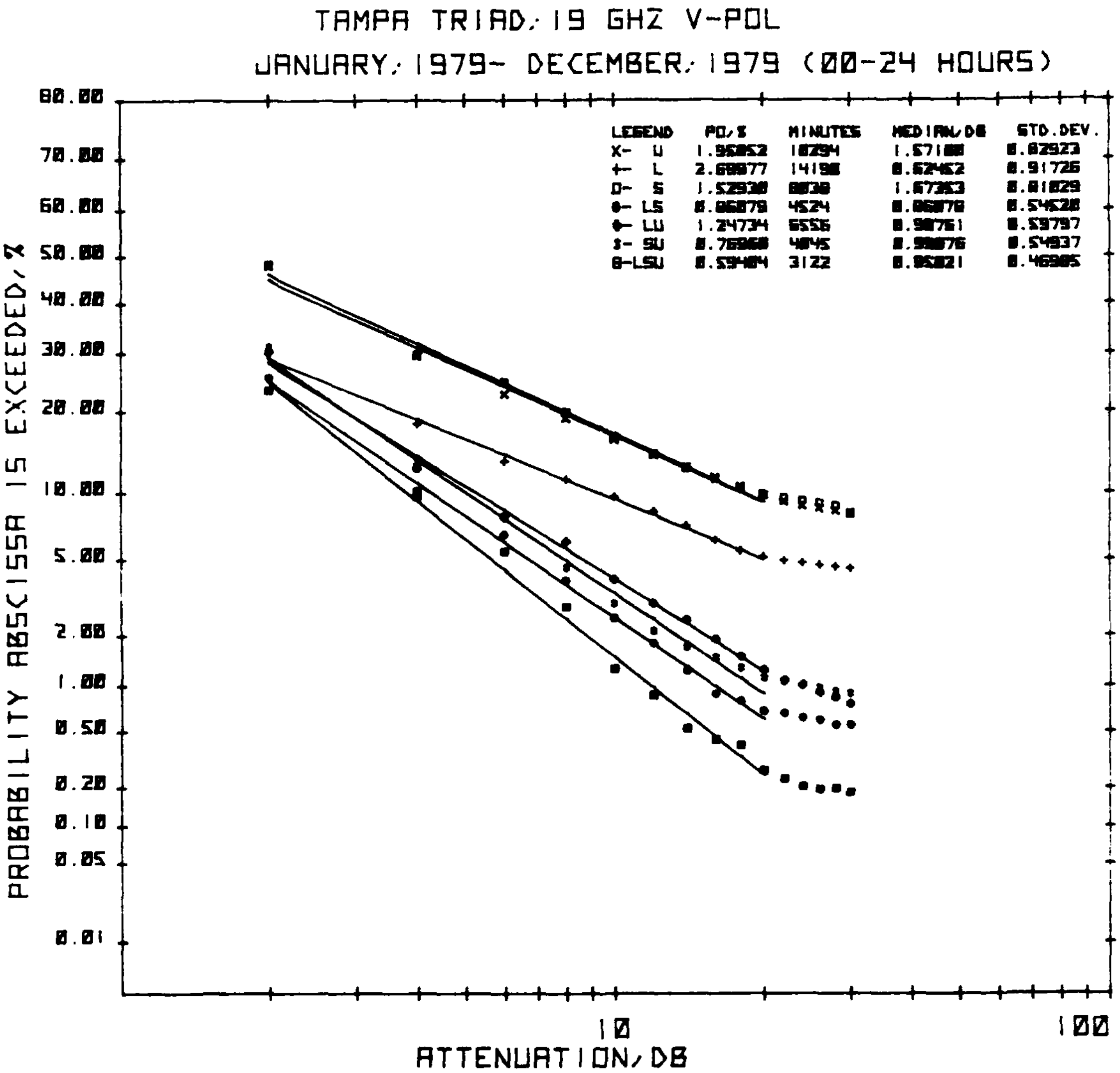

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Figure 6-3. 19-GHz Lognormal Attenuation Plots, Tampa Triad, 1979

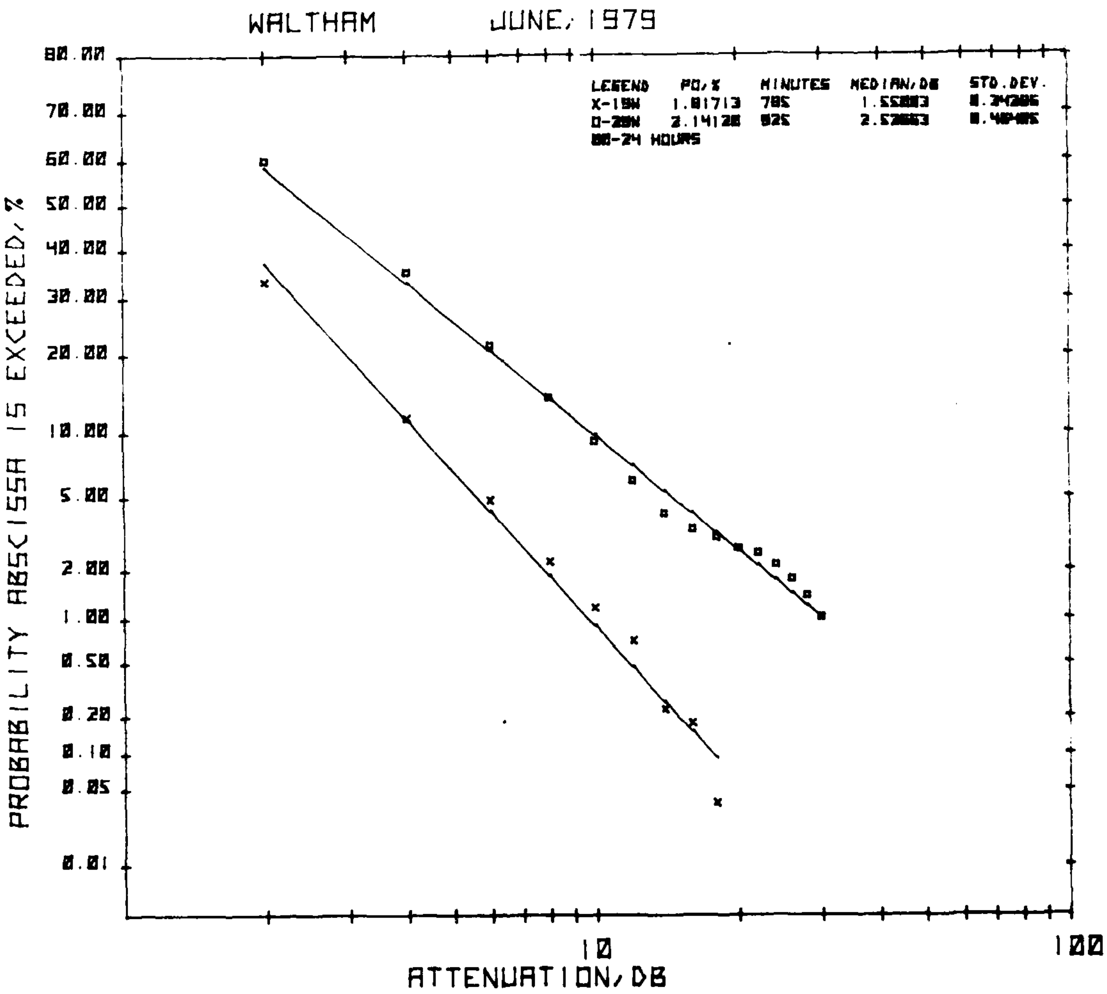

Figure 6-4. 19/29 GHz Lognormal Plots, Waltham, June 1979

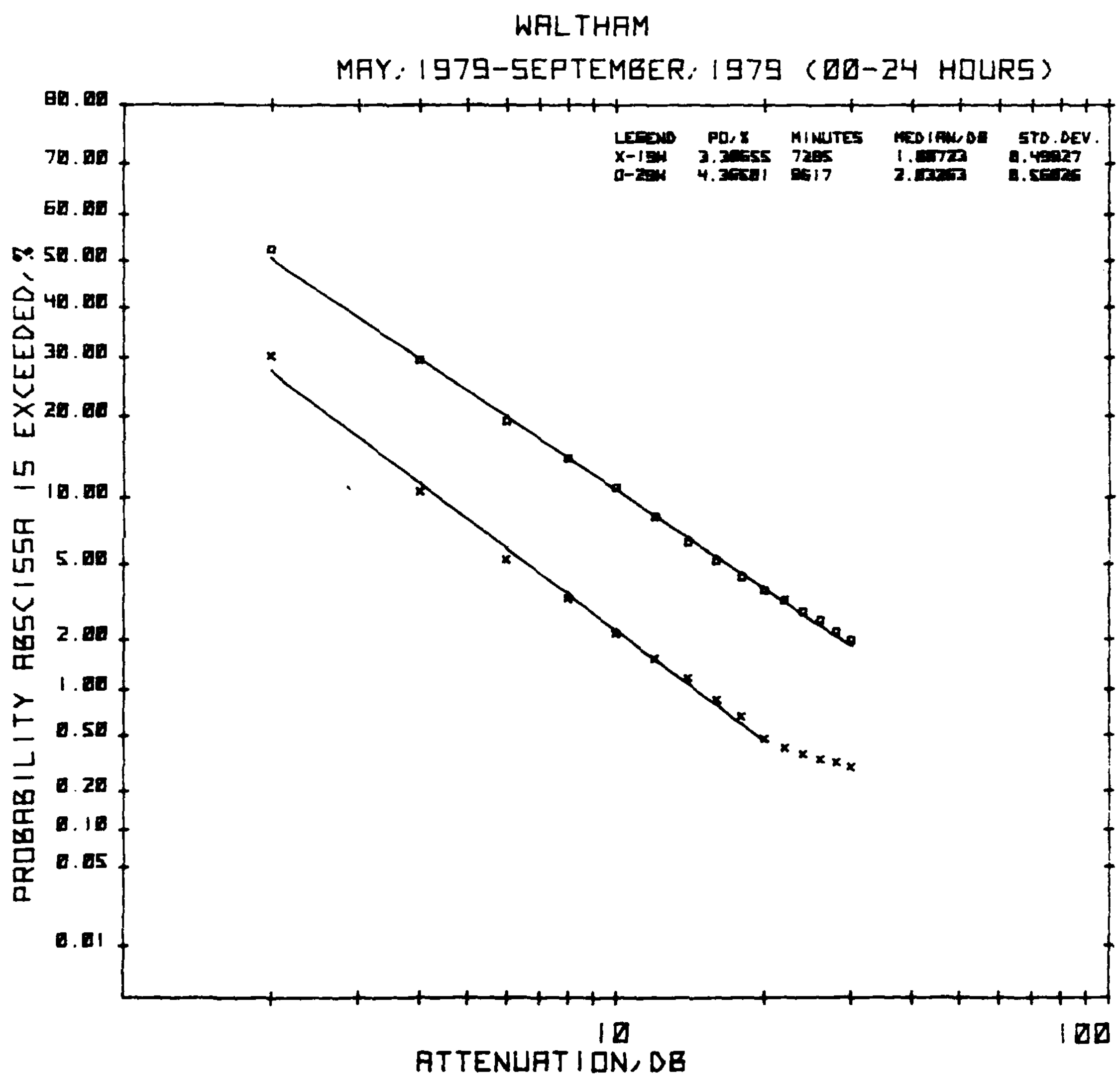

Figure 6-5. 19/29 GHz Lognormal Plots, Waltham, May-Sept 1979

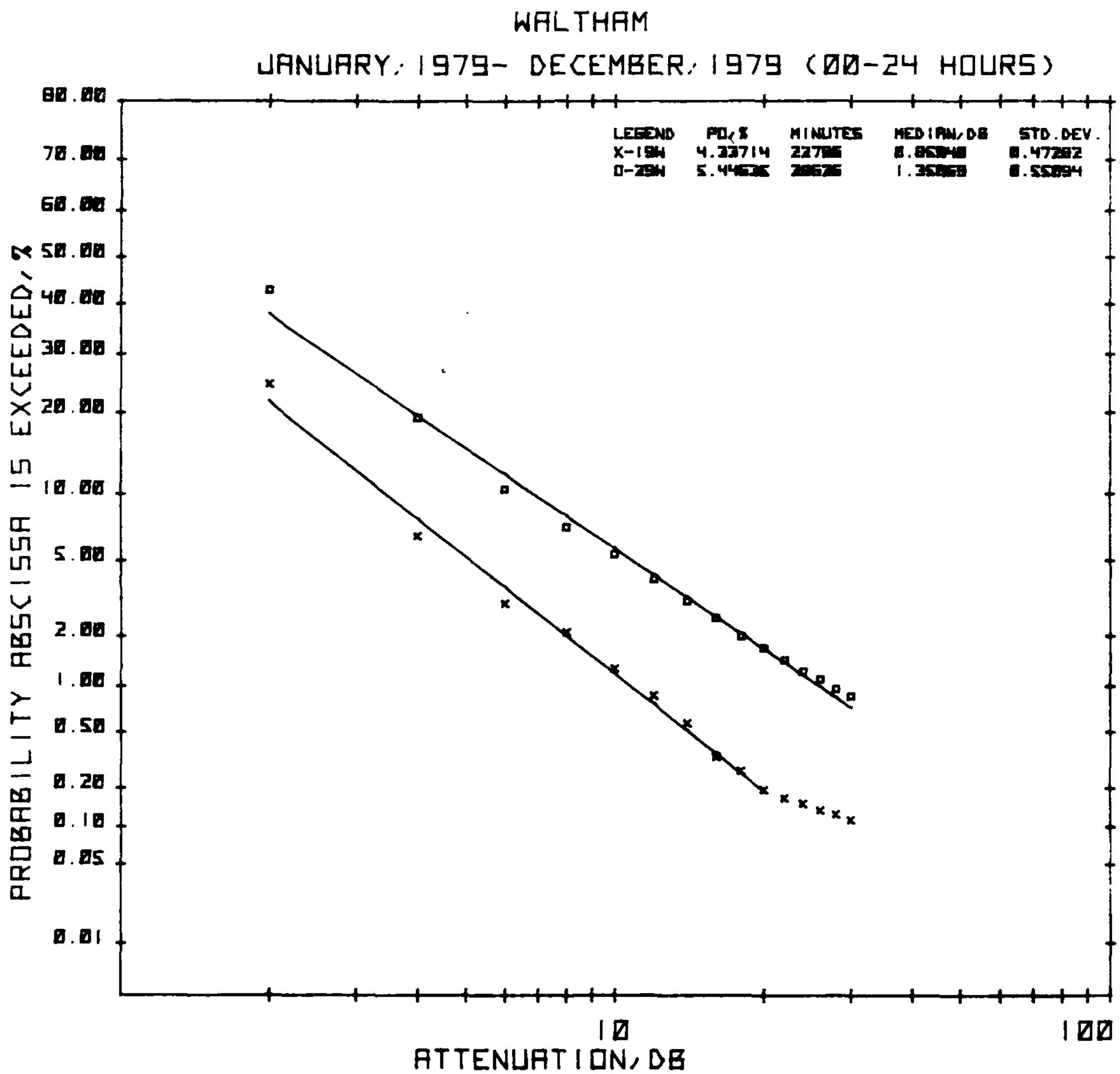

Figure 6-6. 19/29 GHz Lognormal Plots, Waltham, 1979

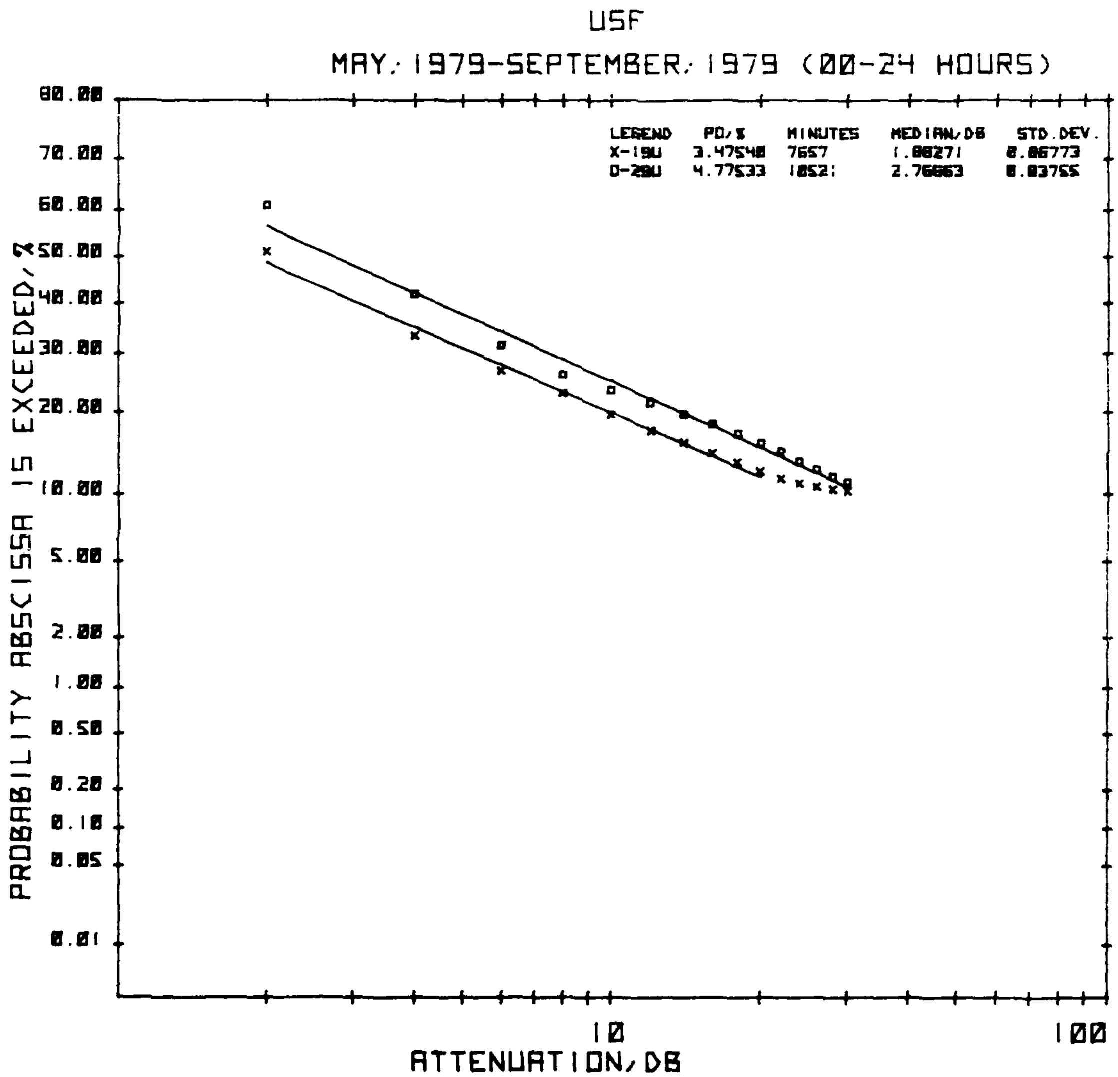

Figure 6-7. 19/29 GHz Lognormal Plots, USF, May Sept 1979

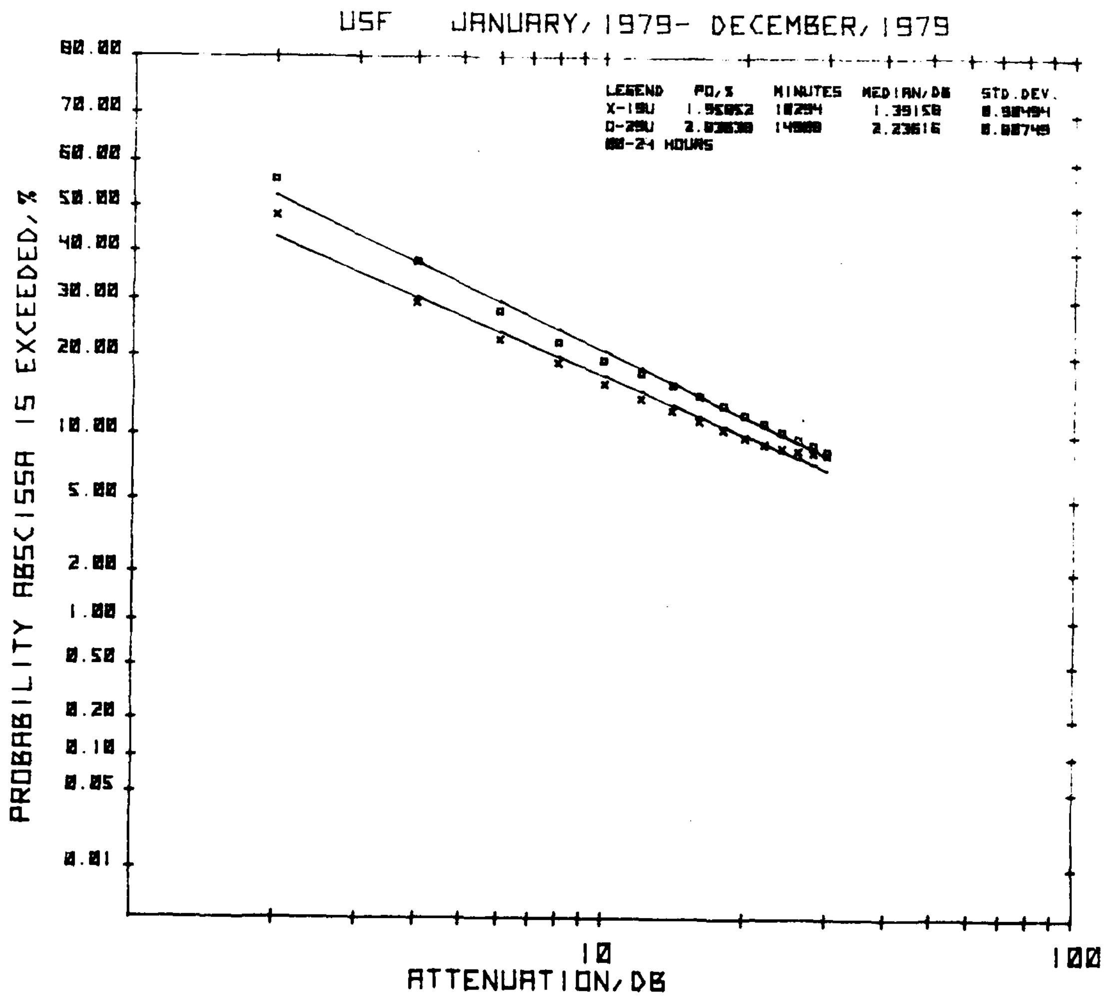

Figure 6-8. 19/29 GHz Lognormal Plots, USF, 1979

SECTION 7
DIVERSITY IMPROVEMENT, TAMPA TRIAD

Allnutt (1978) has given a fundamental discussion of the nature of space diversity for satellite links, defining two measures of diversity improvement: One is diversity gain, measured in dB, that is the apparent gain scaled from the diversity distribution (curve) to the (mean) single-site distribution at fixed outage time or percentage. The other is diversity advantage, the numerical factor describing the reduction in outage (or percentage) for a given rain attenuation (in dB). While Allnutt prefers diversity gain because it may be insensitive to the mean single-site fading, and also permits results from different lengths of observation periods to be compared, diversity advantage has the merit of affording the comparison for a particular rain regime.

In the case of the Tampa Triad, though, the flat tails of the single-site distributions make it impossible to select an outage percentage that intersects both the single-site and the diversity distributions at practical attenuation values. Thus, in this report and in its predecessor we have used diversity advantage. It should be noted that the comparisons made here are for very similar lengths of observation period, e.g., one month, five months, or twelve months.

[A plot of diversity advantage against the selected attenuation level turns out to be a plot of the original attenuation distributions transformed by normalizing to the mean single-site outage time and then taking the reciprocal].

Figures 7-1 and 7-2 show the diversity advantage versus attenuation for May and September 1979. Here, too, May turns out to be a worst month, with September rating very favorably. To cite some comparisons: At the 10-dB attenuation level, diversity advantages of 14.4, 7.9, 5.5 and 3.5 were found for the respective combinations LSU, LS, SU and LU in May, whereas the values 80, 18, 80 and 6 were found for September.

In September, SU diversity is almost as good as that for the triple combination LSU. This indicates that practically all L events coincided with S or U events. From the pair behavior, it can be inferred that more LU coincidences occurred than LS coincidences. This, of course, supports the obvious physical picture that an approaching rain cell of some size is very likely to cover the shortest baseline.

Figure 7-3 shows diversity plot for the May-September 1979 period, and Figure 7-4 for the entire year. Table 7-1 lists the diversity advantage at the 10-dB level of attenuation for the year 1978, 1979 and 1980. Months when "infinite" advantage was noted, were distinguished by either low rainfall or by being dry. LS was the best pair for May, July: SU, for August, September. Overall the best performer seems to be SU. Figure 7-5, the diversity advantage for May-August, 1980, should be compared with Figure 7-3. In 1980 LS is superior to SU.

Hosoya et.al. (1980) quoting Morita (1980) states that for one-year's diversity results at 17 GHz in Japan, using suntracker data, the following power-law relation holds:

$$P_{div} = a\, P_s^{\,b}$$

with P_{div}, P_s being the time percentage for diversity and (mean) single-site, respectively. Here Morita found

$$a = 1.374/S^{0.49}$$

and

$$b = 0.9586 + 0.104\ S^{1/2} \qquad (10 < S < 50\ \text{km})$$

with S the separation.

Application of this power law to the Tampa Triad diversity pairs for the year 1979, and for the summer (May-September) revealed:

<u>Year 1979</u>

$$a = 1.453 - 0.1303S + 0.00383S^2 \qquad (11 < S < 20\ \text{km})$$

$$b = 1 + 0.15 - 0.00026S^2 \qquad (A < 30\ \text{dB})$$

The leading term for the b expression here and in Morita are very similar.

<u>Summer 1979</u>

$$\cdot = 3.02/S^{0.923}$$

$$b = b_o + b_1S - b_2S^2$$

$$b_o = 0.8398 \qquad (11 < S < 20\ \text{km})$$

$$b_1 = 0.2494 \qquad (4 < A < 20 \text{ dB}),$$

$$b_2 = 0.00884$$

The exponent b weakens as S exceeds 16 km showing that the incremental improvement is small, which is what our observations generally on SU and LS tend to show.

The use of the constants in all of the above relations is restricted to the indicated ranges of S and A.

These empirical determinations of diversity effectiveness in Tampa can be used at other radio frequencies: The same range of percentages can be taken, but of course, the related attenuations will be different. There may be some relatively weak frequency dependence* of effective path length as discussed by (Kheirallah, 1980), and also because different beam widths will likely apply. Neglecting these, the attenuation range involved at another frequency will be about as predicted by the ratios of specific attenuation rates. An idealized empirical form for the diversity advantage (I) can be constructed from the log-normal distribution that describes P_s. Here we assume both single sites have the same distribution so

$$P_s = (P_o/2) \text{ erfc } (w/\sqrt{2}) = P_o \, Q(w)$$

as described in Section 6. [Q(w) is tabulated in Abramovitz and Stegun [1964]]

Then by the power-law relation above, the diversity advantage is,

$$I = P_s/P_{div} = a^{-1} \, P_o^{\,1-b} \, [Q(w)]^{1-b}$$

This expression may be calculated exactly if P_o and $w = (\log A/A_m)/S_A$ are known.

Taking parameter values from Figure 6-3 with $A_m = 1.5$ dB, $S_A = 0.9/\log_{10}e = 2.07$ which are approximate values for sites S or U, we generate the curves in Figure 7-6. These curves, if replotted on a semi-log plot would be similar to those in Figure 7-4. At the 10-dB level, the diversity advantage (I) in this resulting empirical model increases only 63% if the spacing is nearly doubled, from S = 11 to S = 20 km. This suggests that very little would be gained at the 10-dB level by an increase of S from S = 20 to S = 25 km. These model curves are idealized since they assume (1) identical log-normal distributions with equal P_o (fraction of time attenuation is encountered) and (2) the spacing dependence determined from the annual distribution, Figure 2-1.

*See also the discussion in Section 2.

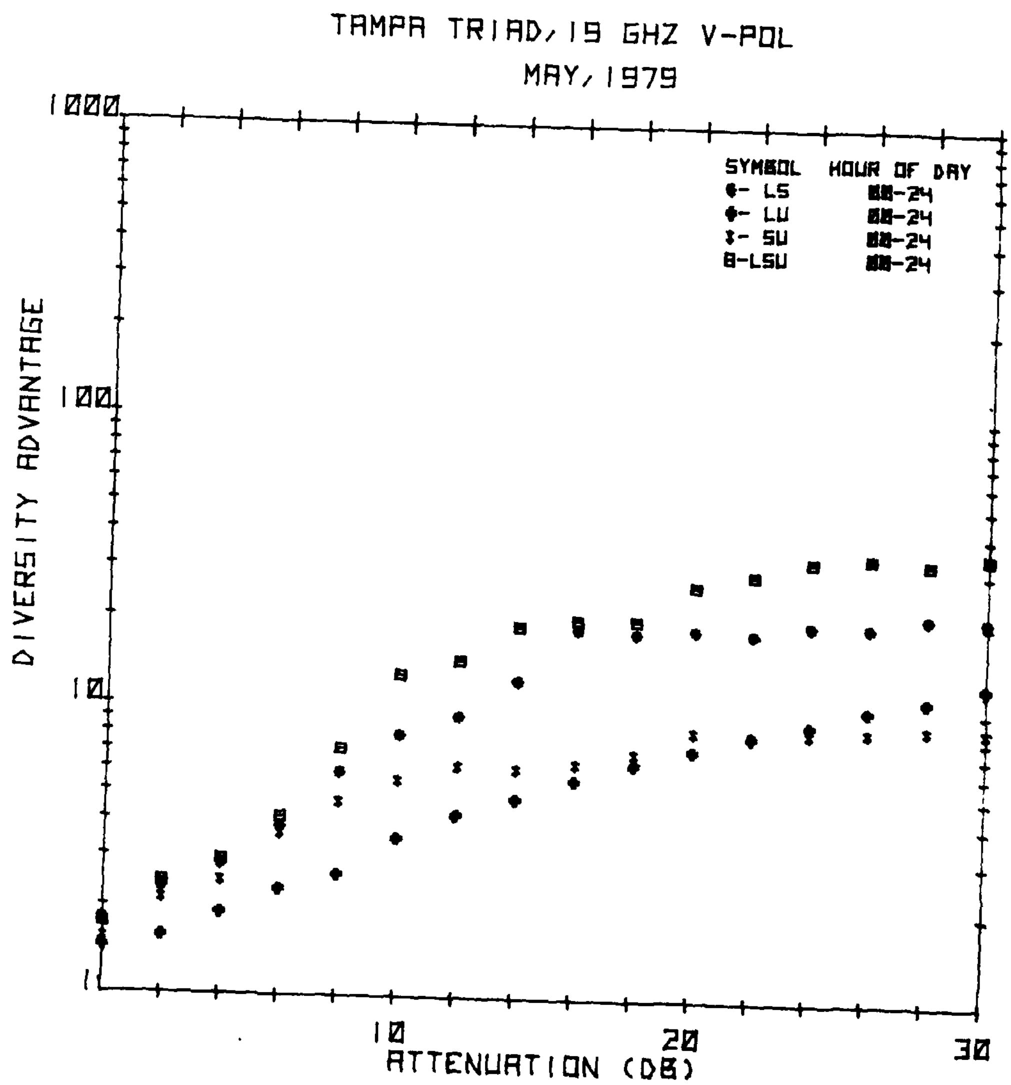

Figure 7-1. 19-GHz Diversity Advantage, Tampa Triad, May 1979

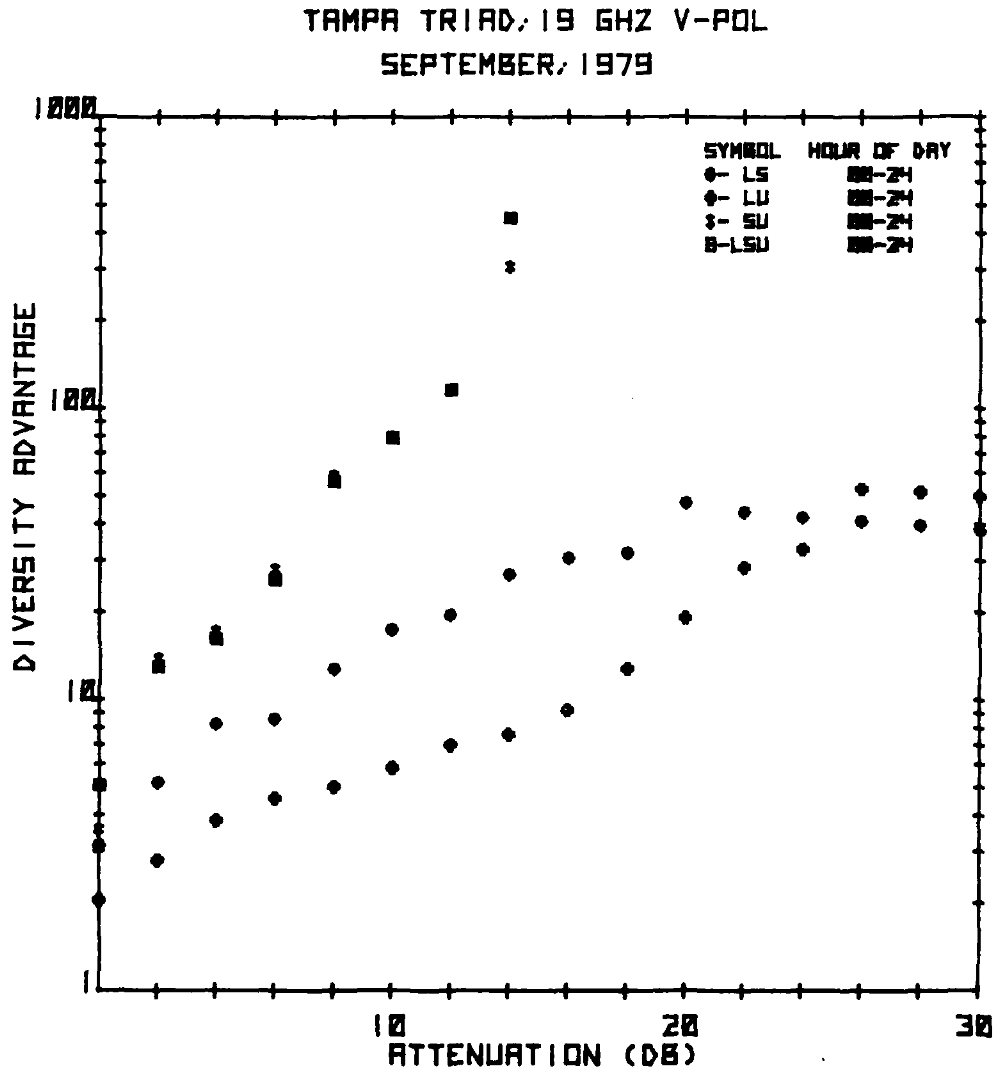

Figure 7-2. 19-GHz Diversity Advantage, Tampa Triad, Sept. 1979

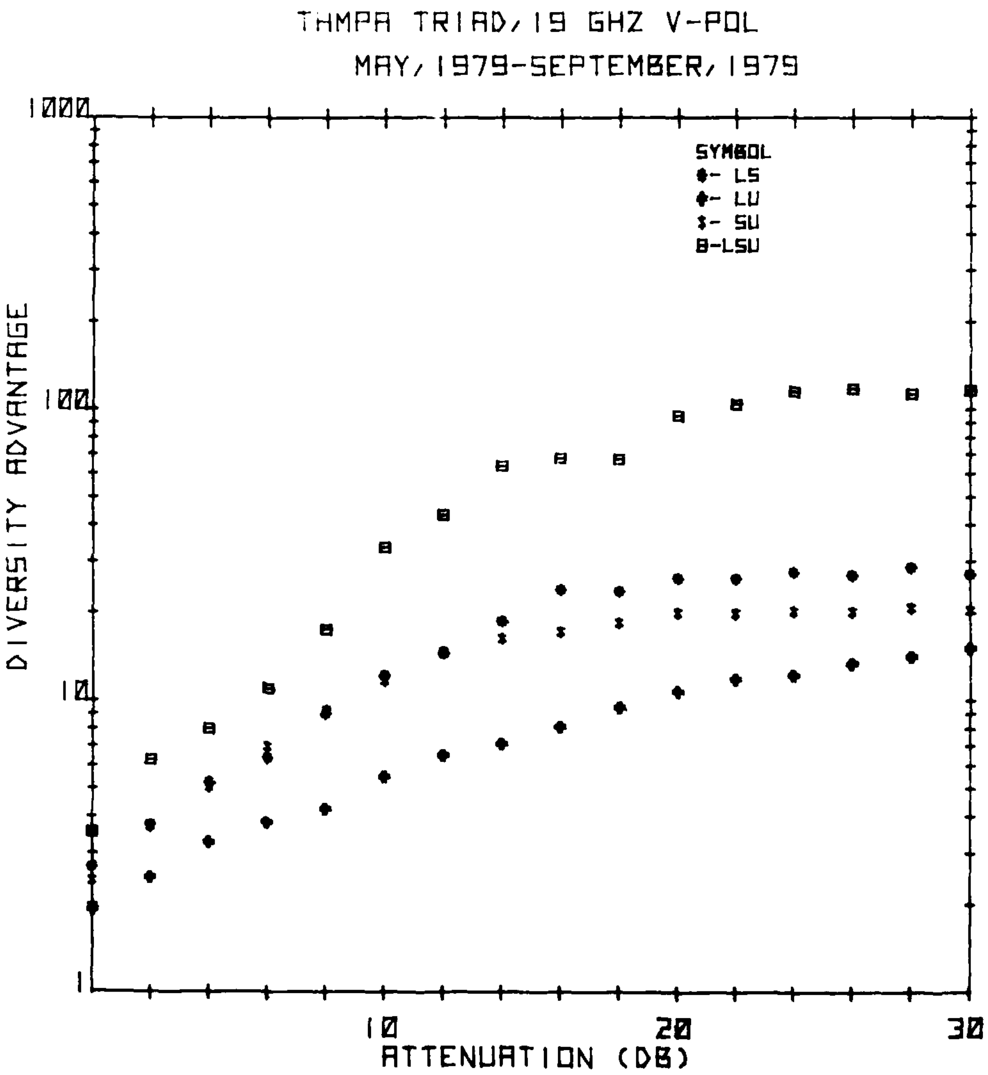

Figure 7-3. 19-GHz Diversity Advantage, Tampa Triad, May-Sept 1979

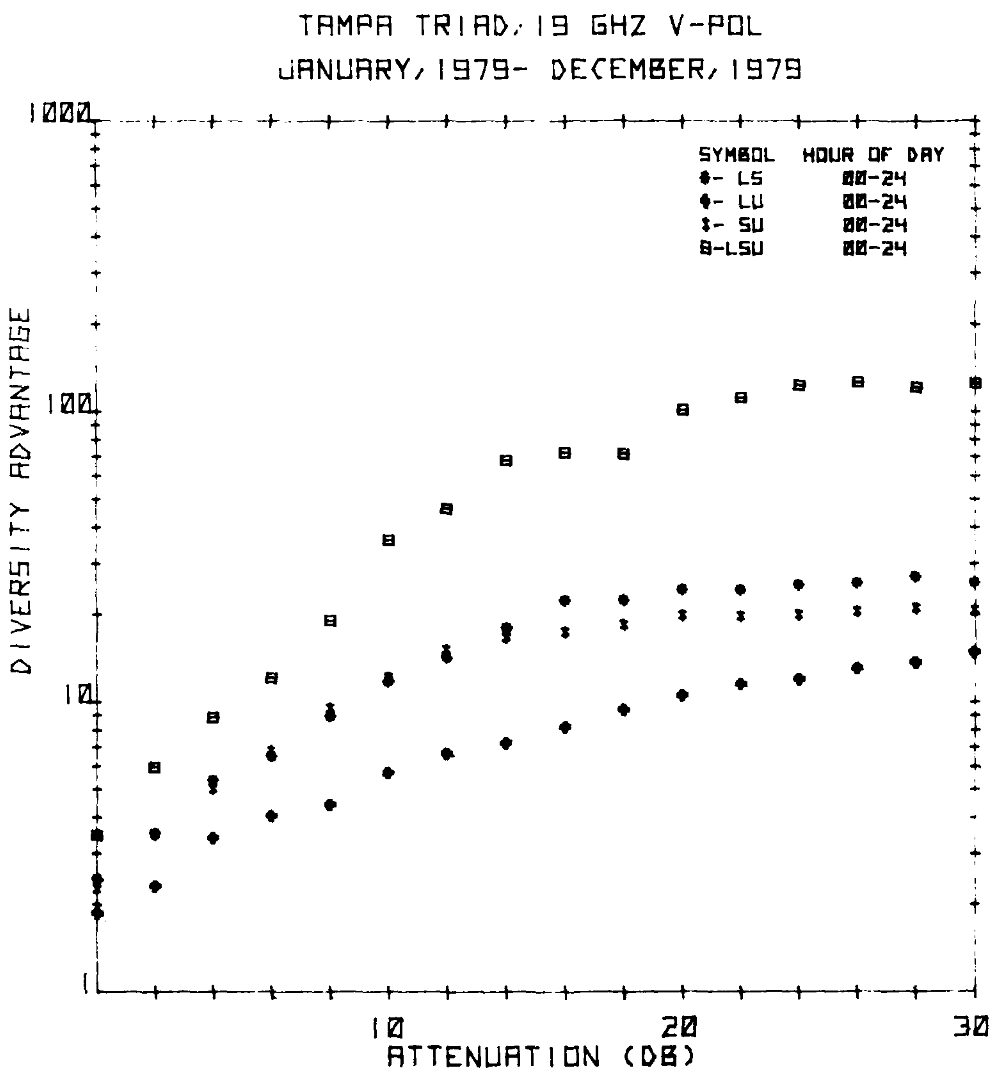

Figure 7-4. 19-GHz Diversity Advantage, Tampa Triad, 1979

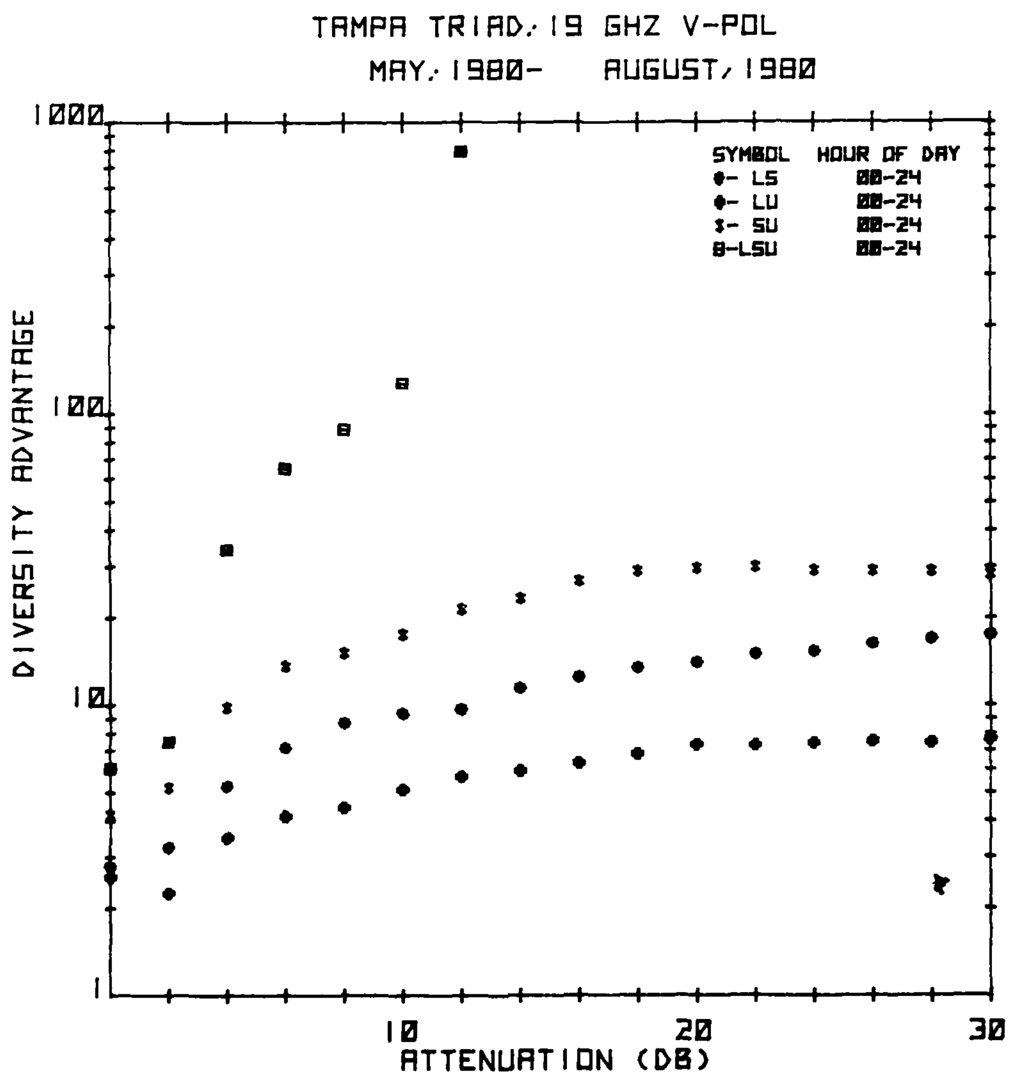

Figure 7-5. 19-GHz Diversity Advantage, Tampa Triad, May-Aug 1980

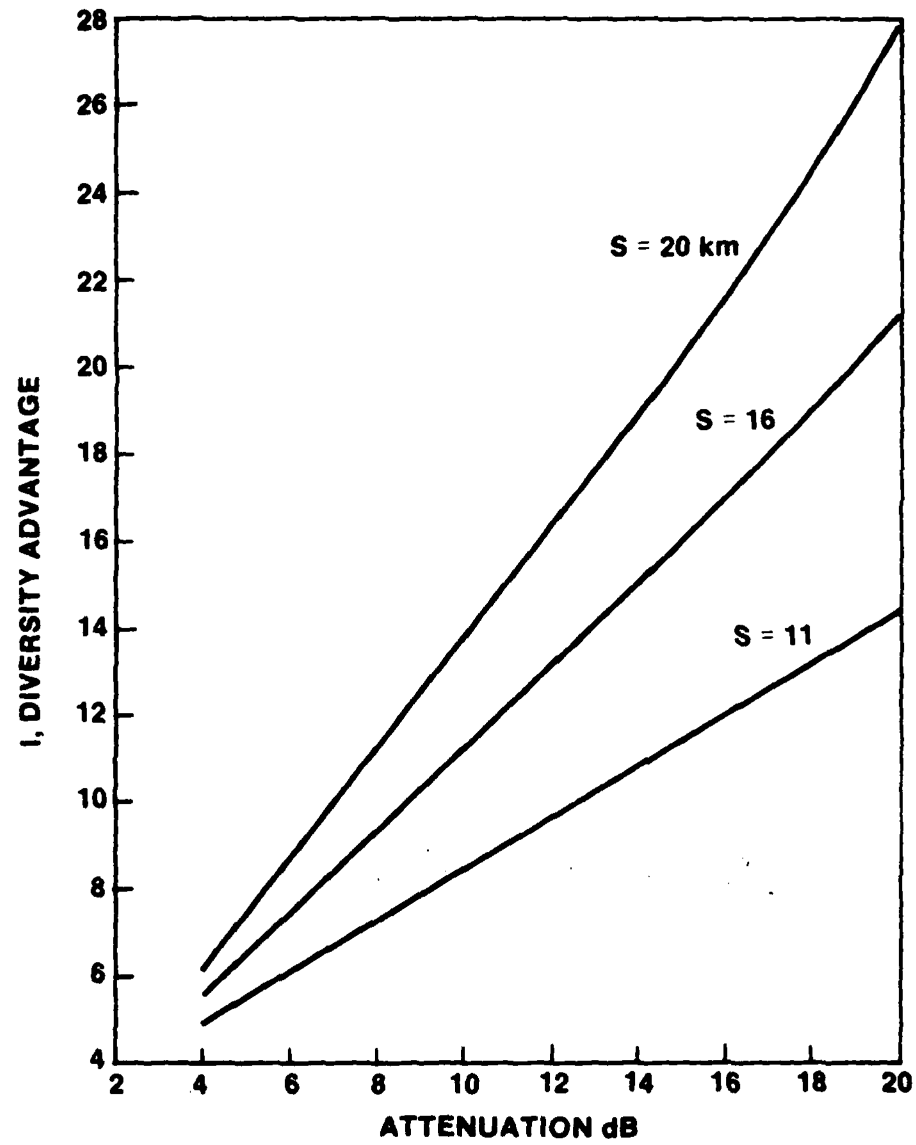

Figure 7-6. Empirical Model Form of Diversity Advantage I -Tampa Triad 1979-

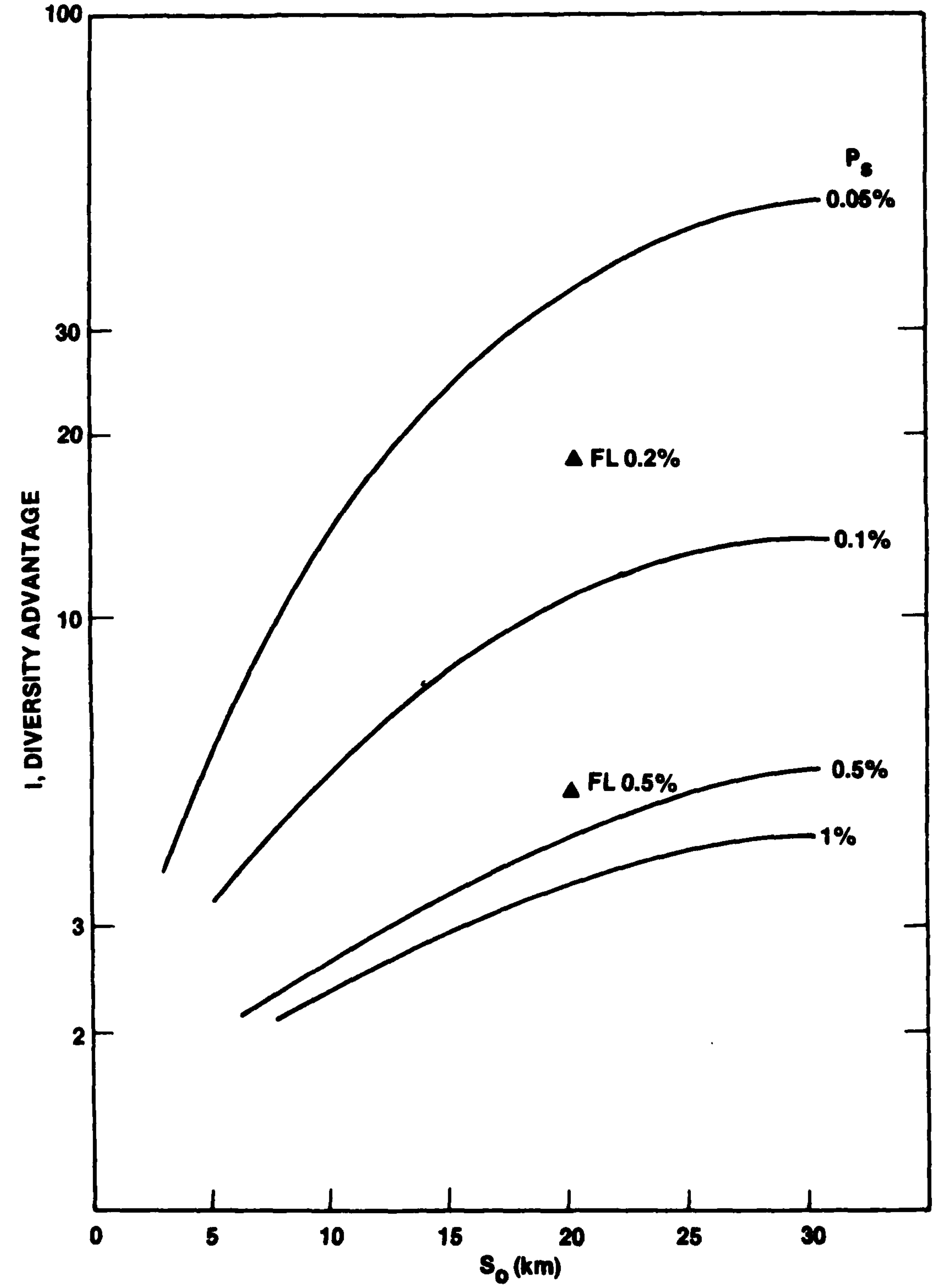

Figure 7-7. Diversity Advantage vs Spacing Based on CCIR Report 564-1

TABLE 7-1
COMPARISON OF DIVERSITY ADVANTAGE IN 1978 AND 1979
AT 10-dB ATTENUATION LEVEL, TAMPA TRIAD

Month	LS			LU			SU			LSU		
	1978	1979	1980	1978	1979	1980	1978	1979	1980	1978	1979	1980
January	X	7.5	∞	X	∞	∞	X	∞	∞	X	∞	∞
February	X	5.8	15.7	X	6.1	8.6	X	17.0	∞	X	∞	∞
March	X	∞	22.9	X	∞	6.9	X	∞	4.0	X	∞	∞
April	∞	∞	∞	∞	∞	38.0	2.6	∞	22.4	∞	∞	∞
May	3.3	7.9	17.8	2.2	3.5	3.6	2.0	5.5	36.1	5.6	14.4	41.6
June	∞	∞	10.1	∞	9.2	16.0	∞	∞	27.7	∞	∞	∞
July	72.0	16.6	13.0	21.0	12.0	4.9	174.0	5.4	39.1	∞	∞	∞
August	3.8	12.0	4.8	2.6	6.0	4.4	6.8	26.0	7.1	9.6	60.0	∞
September	5.6	18.0	X	11.5	6.0	X	∞	80.0	X	∞	80.0	X
October	∞	∞	X	∞	∞	X	∞	∞	X	∞	∞	X
November	NR	∞	X	NR	∞	X	NR	∞	X	NR	∞	X
December	9.8	∞	X	6.4	∞	X	∞	∞	X	∞	∞	X

NOTE: NR = No Rain; X = System Not in Operation.

Morita and Higuti (1978) analyzed the correlation of path-averaged rain rates for separated sites, with different orientation to a satellite. With assumed point rain-rate correlation coefficient $\rho = \exp(-\alpha\sqrt{D})$ where D is the diversity separation, and α is a parameter characteristic to a region, they found correlation for the path-averaged case to be essentially independent of orientation geometry for elevation angles θ greater than about 15°. Their analysis shows that $\rho \simeq 0.3$ for D = 20 km and $60° < \theta < 40°$, but is a weak function of D in the range 15-25 km.

Morita and Higuti (1978) also tabulate reported results of observation of diversity effects. We recast their table (see Table 7-2) so the diversity advantage (I) is shown explicitly against single-site outage percentage, adding in the Tampa Triad results for 1979. For single site outage probability P_s = 0.2%, I > 10 only for the BTL GA long baselines, for the Tampa Triad LS pair, and for the BTL NJ 30 km baseline. For this comparison, therefore, it appears that the Tampa LS-pair performance is probably as good as might be expected for the baseline length involved. [The table also shows that in the UK diversity advantage (I) is almost always much less at P < 0.2% than is found in the USA or Japan, reflecting prevalence of widespread weak rain conditions in the UK.]

In CCIR Report 564-1 (1978) the data tabulated by Morita and Higuti (1978) has been organized into a graphical form in which the joint probability P_{div} is plotted against the diversity site spacing S, and upon this figure model curves parametric in P_s are fitted. In our report and in much of the diversity work of others the functional interest is in the diversity advantage (I) versus S, for fixed P_s. Such a family of curves would be the analogue of the diversity gain curves originally formulated by Hodge (1976) and would be useful in rain regimes and frequency ranges where diversity gain should not be utilized. (See discussion in Kaul, et al, 1980). Using CCIR Report 564-1, an approximate form of the I vs. S family was found as:

$$\log I = (\log I_\infty)\,(1 - \exp(-S/S_o))$$

Here S_o is a characteristic distance beyond which I grows more slowly. I_∞ is the asymptotic level of I and is a function of the single-site probability P_s. We found tenable values as follows:

P_s	S_o = 10 km I_∞	$\log I_\infty$
0.05%	60	1.78
0.1	15	1.18
0.5	6	0.78
1.0	4.5	0.65

In Hod- (1976) the diversity gain has the form

$$G_{div} = A_1 \, (1 - \exp(-S/S_1))$$

where A_1 is another exponential function, of the attenuation A alone, and $S_1 = S_1(A)$. S_1 seems to be limited to (1/0.46) = 2.2 km at most, in contrast to S_o = 10 km and above.

Figure 7-7 shows the I vs. S curves as transformed from CCIR Report 564-1. The Florida 1979 data for 20 km listed in Table 7-2 are plotted in this figure. The 0.5% is fairly close to the curves, but as noted earlier, the I = 18.0 value for 0.2% is much higher than the experience elsewhere upon which the curves have been based. (The SU baseline - 16 km - also gave I = 18.0, approximately, for P_s = 0.2%). The flat tails of the Tampa distributions, of course, do not enable determination of I for P_s < 0.2%.

TABLE 7-2

DIVERSITY ADVANTAGE (I) VS SINGLE-SITE OUTAGE PERCENTAGE

Location (Months)	GHz	Elev (deg)	km	Single-site Outage (%)			
				1	0.5	0.2	0.1
ECL, Tokyo (12)	18	45	14.3	-	-	5.9	62.5
RRL, Tokyo (6)	35	45	15	3.8	4.2	6.0	8.3
BTL, NJ (5)	16	30	5 11 14	1.7 2.0 2.2	2.1 2.9 2.9	2.1 10.0 5	2.5 41.7 11.1
BTL, NJ (12)	16	30	11.2 19.2 30.4	2.5 2.9 5.6	3.1 5 8.3	3.3 10.0 12.5	10 12.5 28.5
BTL, NJ (10)	15.5	30	19	2.5	2.8	5.7	15.4
BTL, GA (24)	17.8	38.2	15.9 31.2 47.1	2.9 4.5 5.0	4.2 8.0 10.4	9.1 33.3 38.5	- - -
BTL, CO (24)	17.8	42.6	33.3	-	-	5.1	10.0
GTEL, FL (12)	19	57	20	-	5.0	18.0	-
Appleton Lab, UK (14)	11.6	29.5	7.1 16.4 18.2 23.6	- - - -	- - - -	2.9 5.7 5.0 5.7	3.3 6.3 5.0 12.5

GTEL, FL data are from this report.
Rest are based on Morita & Higuti (1978).

SECTION 8
ATTENUATION DISTRIBUTIONS BY DAILY TIME BLOCKS

Only the summer-month distributions were considered for the study of occurrence of attenuation in various time blocks. Six-hour time blocks v e chosen 00-06; 06-12; 12-18 and 18-24 hr, local time (EST).

Figures 8-1 through 8-7 show attenuation distributions for May through September for these four time blocks. In general, the 00-06 time block shows lowest outage percentage. Considering only single-site distributions, maximum outage occurs between noon and 18 hr local time. With diversity, the time blocks of maximum outage differ according to the diversity combination. For LS, maximum outage occurred between 06-12; for LU, 12-18, much like a single site; for SU, 18-24; and finally, for LSU, 12-18, reflecting the role of the LU combination.

The time block differences in maximum outage among the various combinations is another aspect to the varying diversity effectiveness for these summer months.

Table 8-1 summarizes the results for the four time blocks. Maximum outage is about 10 times the minimum outage. Listed also are the 00-24 hr outage percentages. Note that L and S have almost identical 24-hr outage percentages.

The results indicate that even with diversity operation, a given communication system in the southeast USA may characteristically show a diurnal variation in outage performance or attenuation severity. With a particular diversity combination (LS in this instance) the time block of most outage may possibly be shifted from the afternoon to a less-busy time block (for business activities).

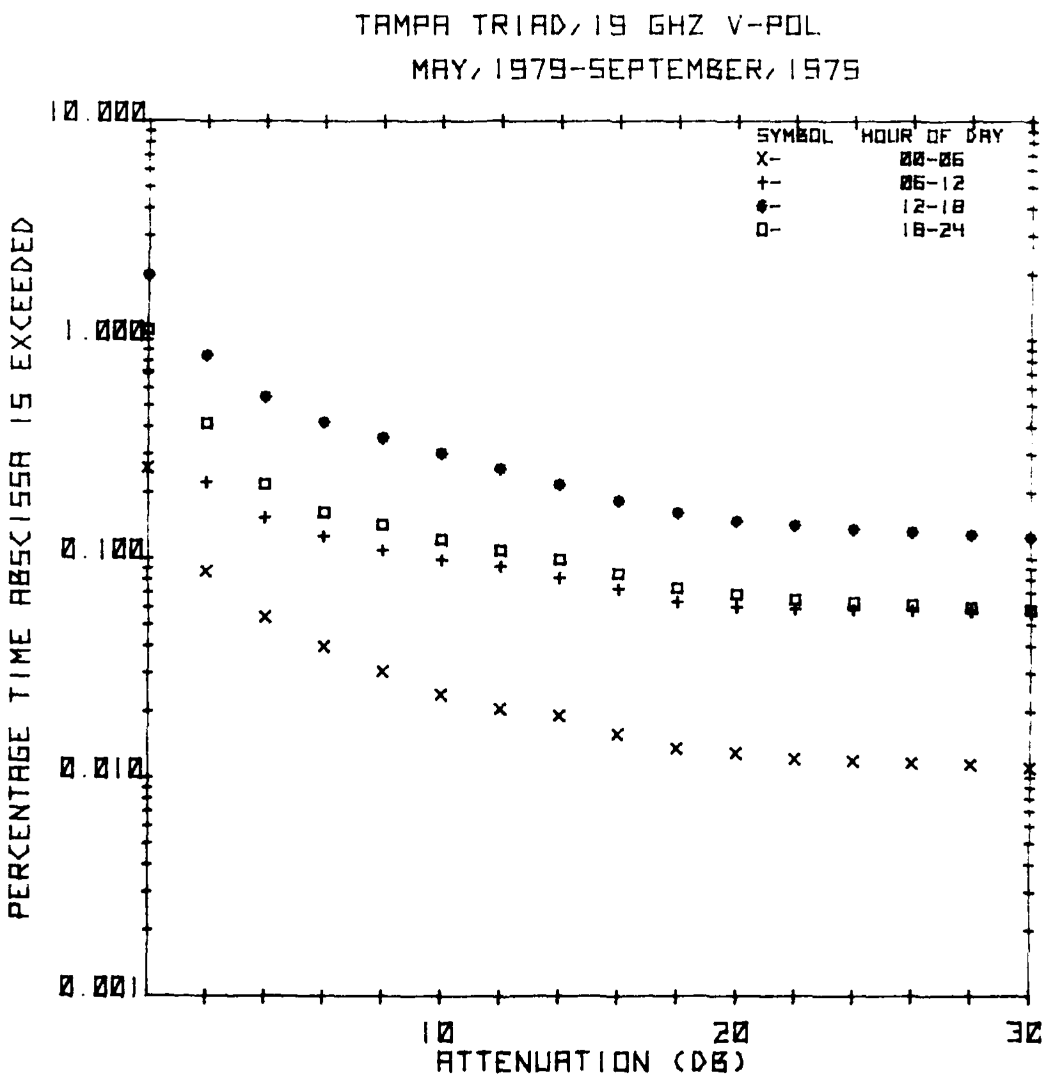

Figure 8-1. Attenuation by Time Block, Lutz, May-Sept 1979

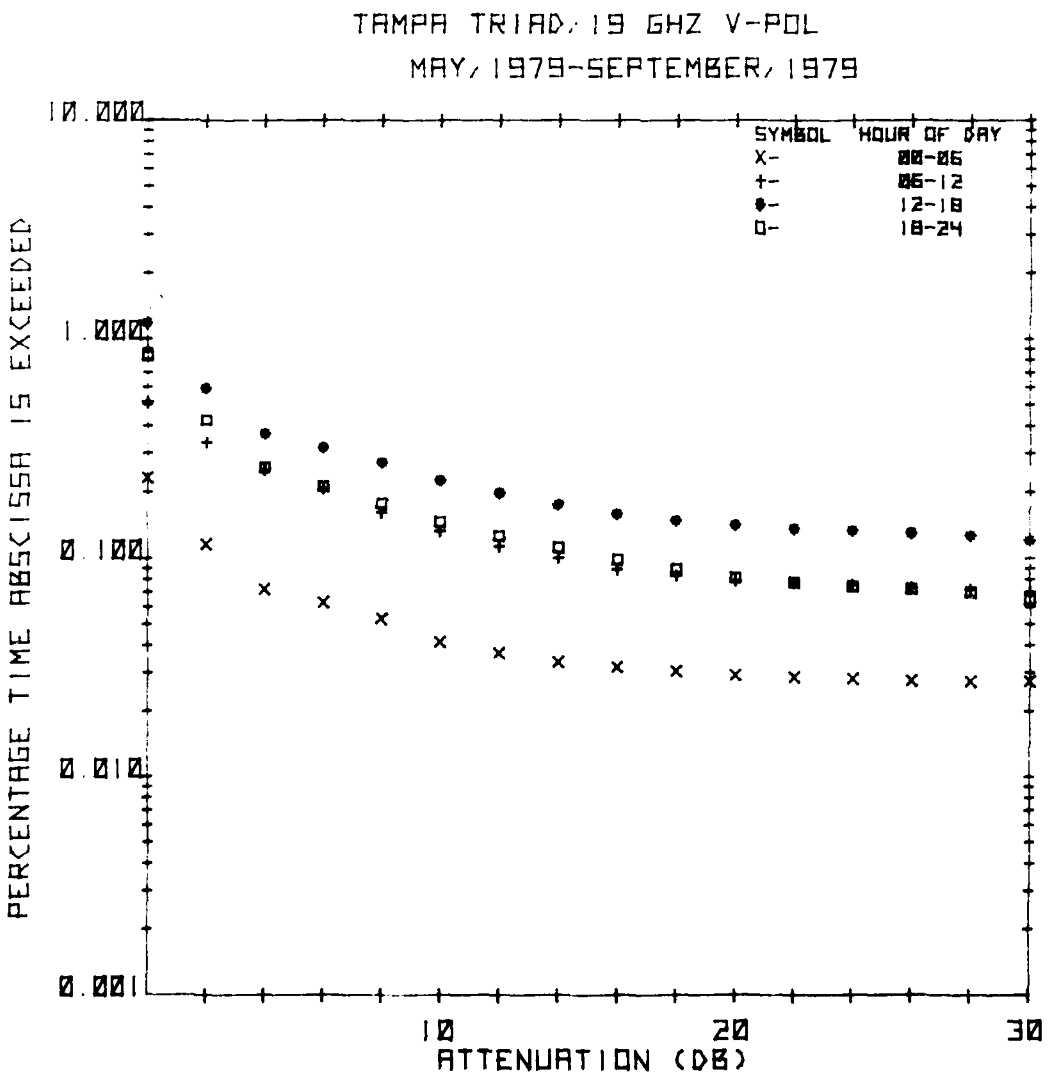

Figure 8-2. Attenuation by Time Block, Sweetwater, May-Sept 1979

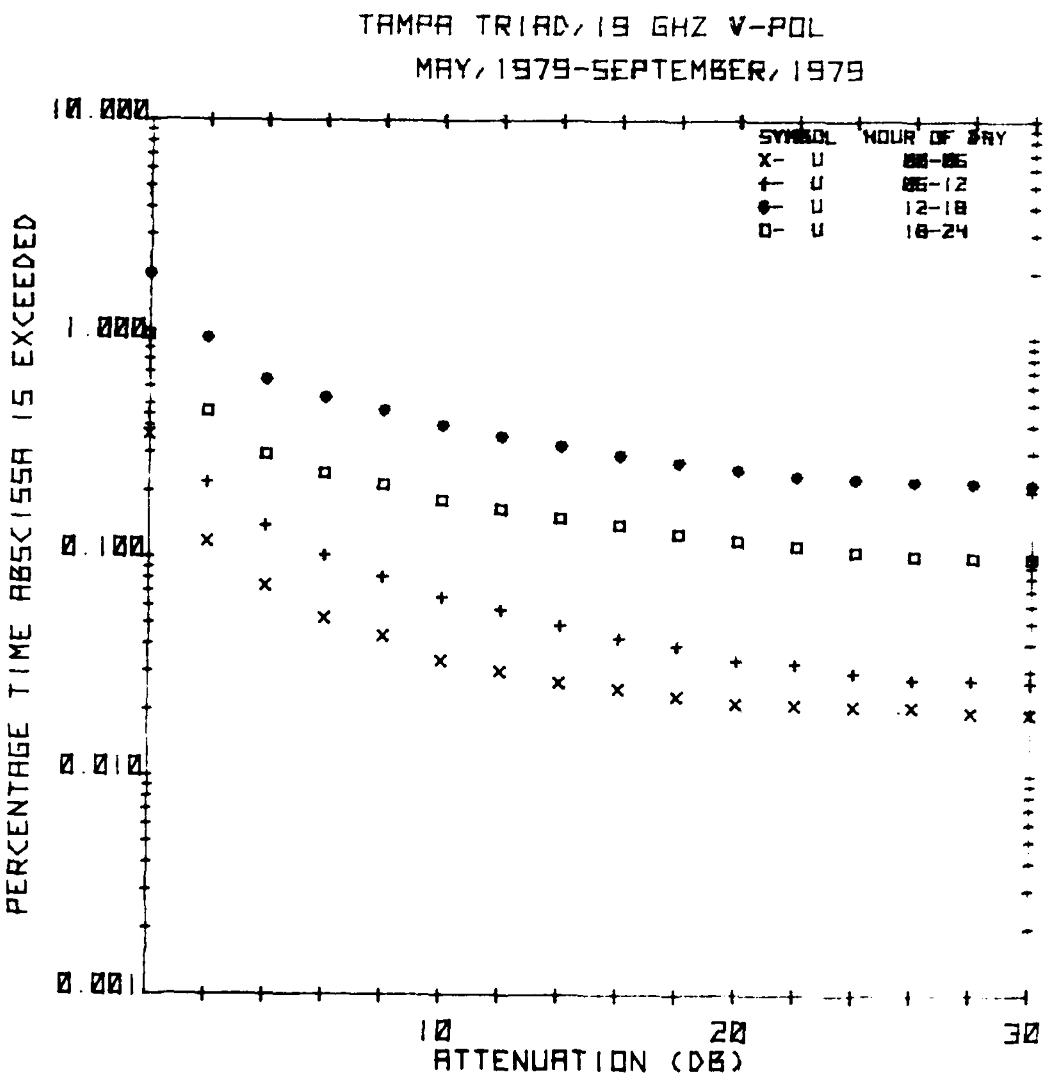

Figure 8-3. Attenuation by Time Block, USF, May-Sept 1979

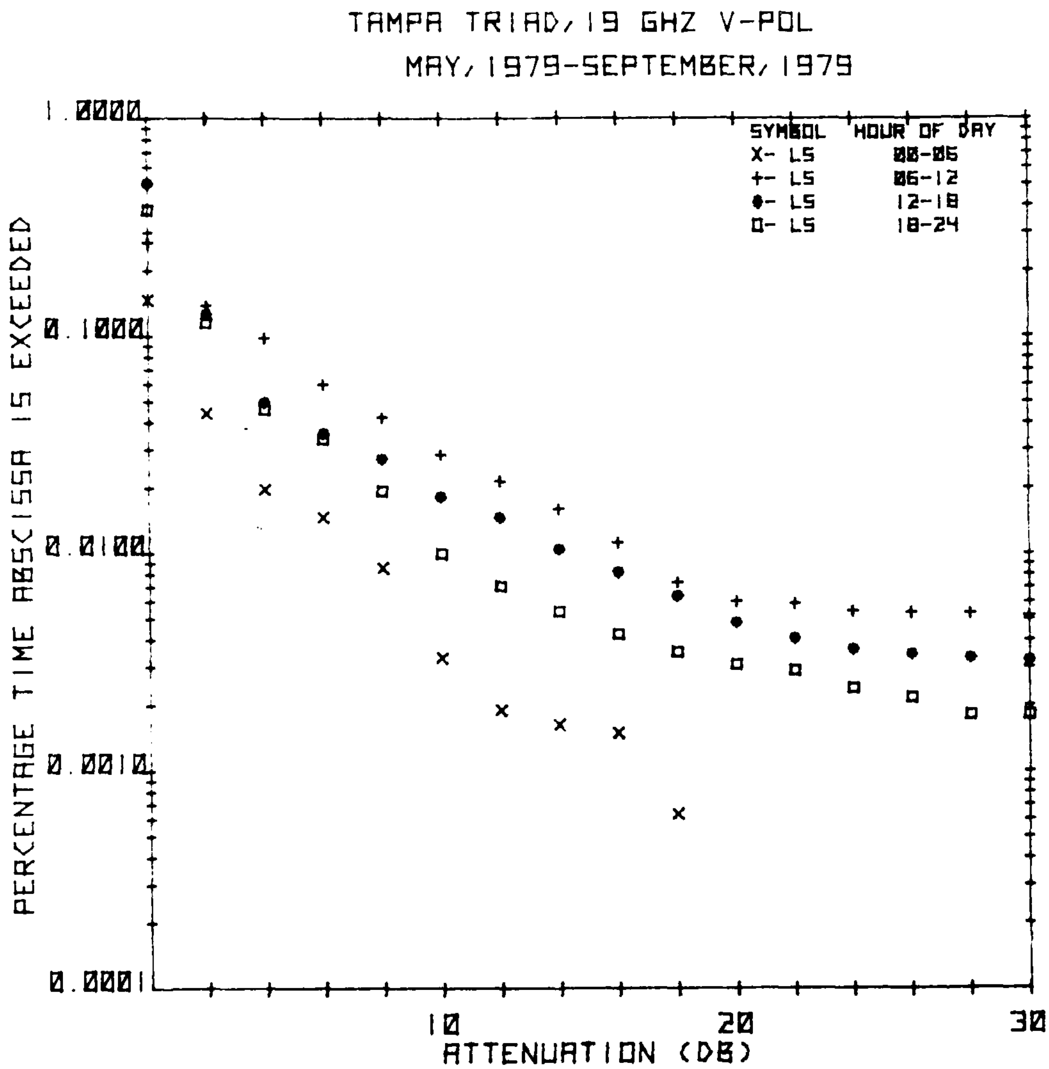

Figure 8-4. Attenuation by Time Block, LS Pair, May-Sept 1979

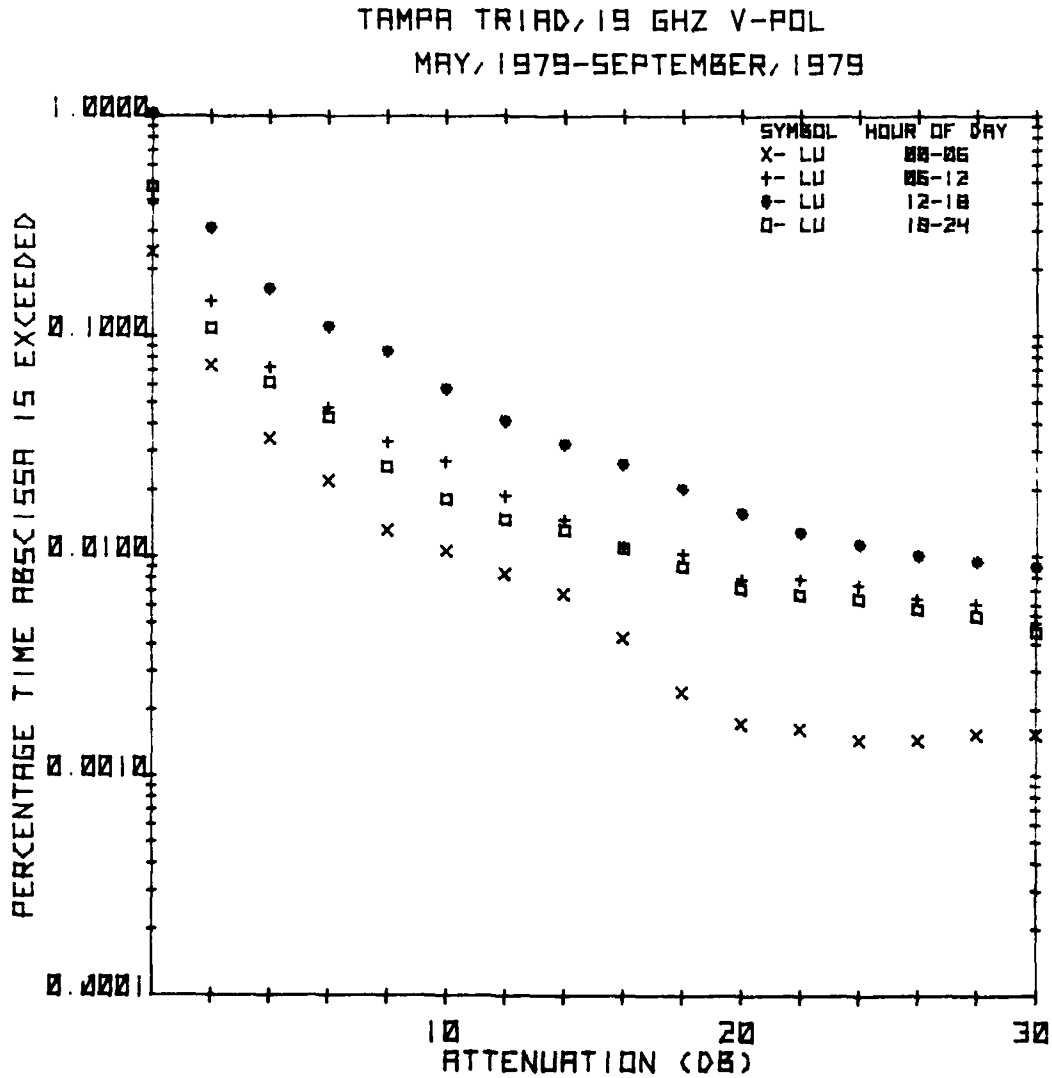

Figure 8-5. Attenuation by Time Block, LU Pair, May-Sept 1979

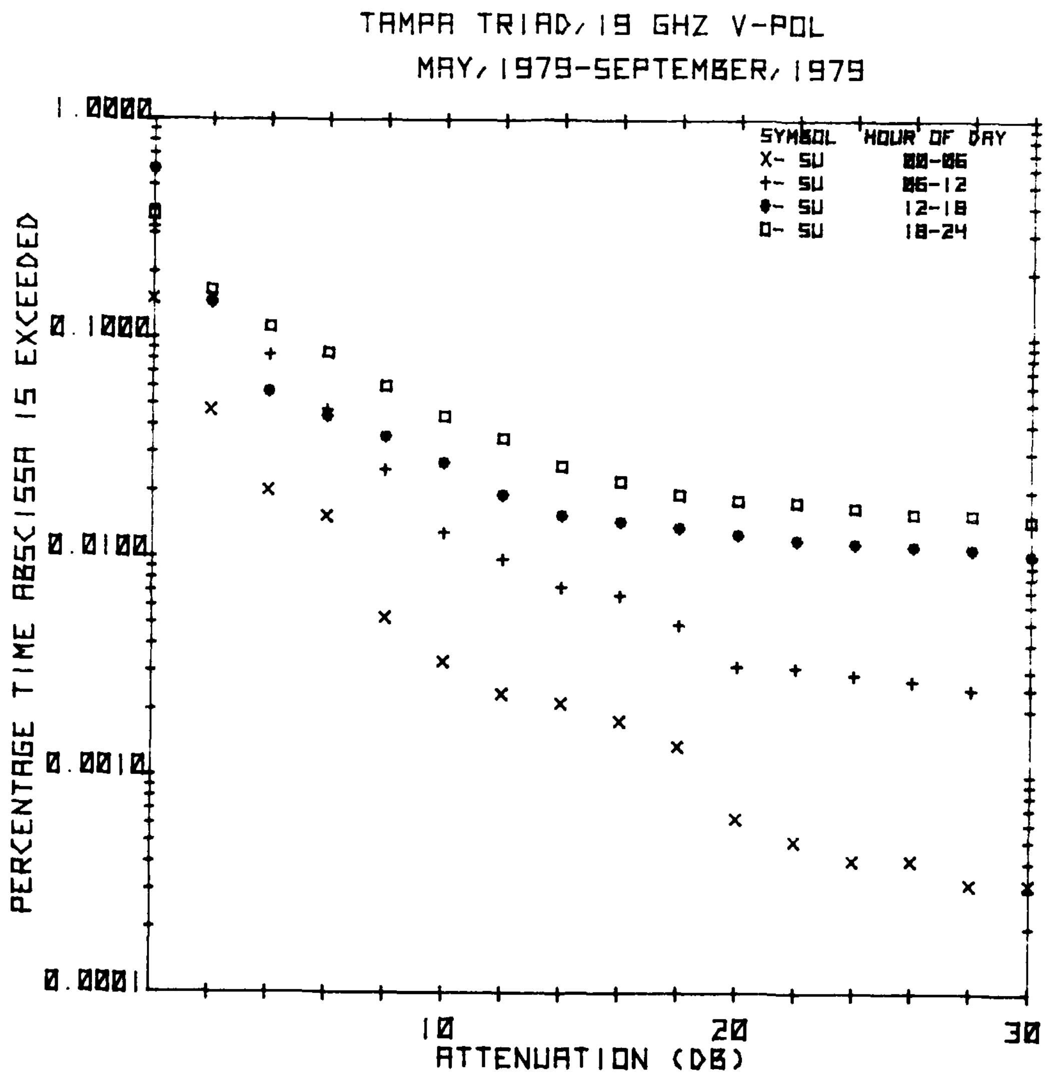

Figure 8-6. Attenuation by Time Block, SU Pair, May-Sept 1979

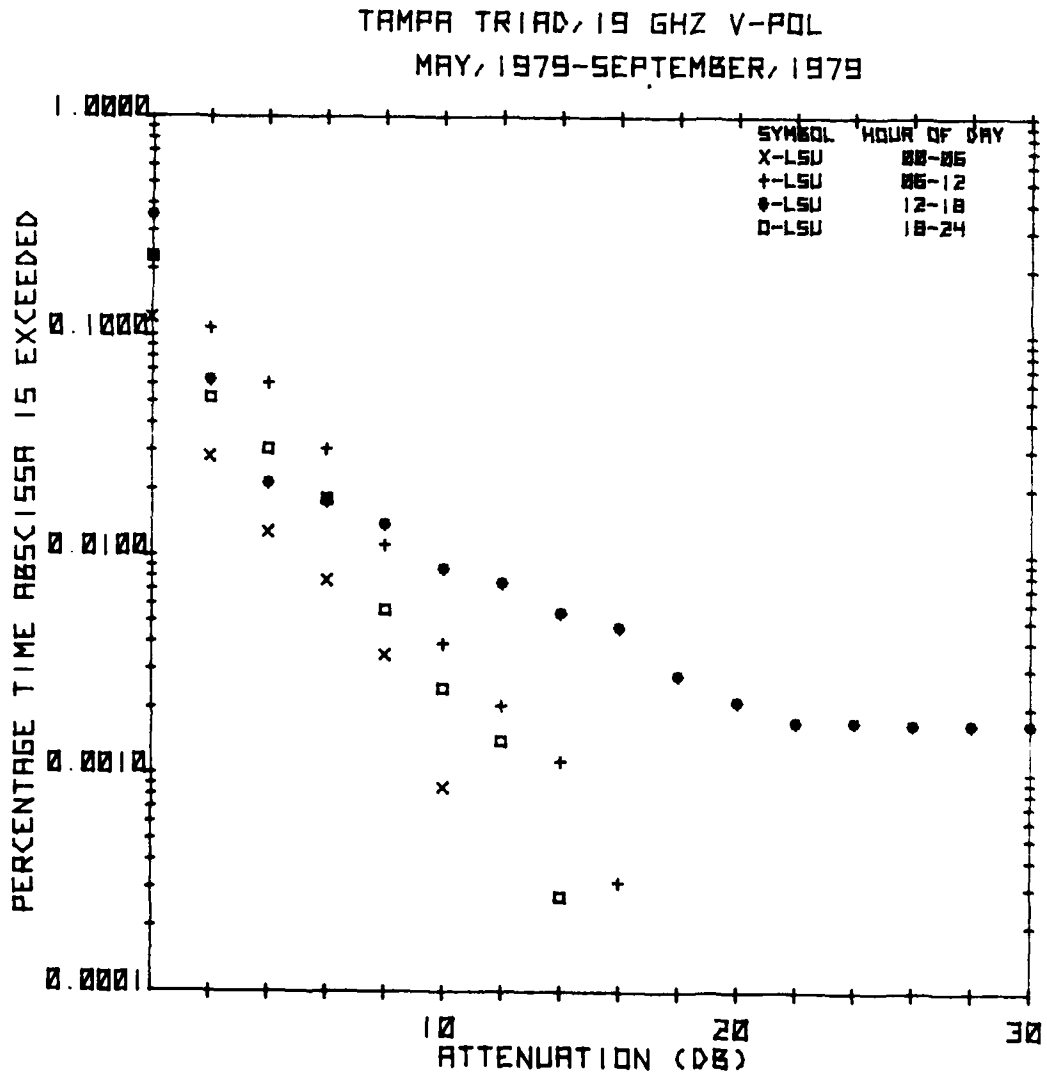

Figure 8-7. Attenuation by Time Block, LSU, May-Sept 1979

Table 8-1

Summary of Percentage Outage Time
at 10-dB Attenuation Level
Tampa, May-September 1979, by Time Block

	---- Local Time Block ----				
Site(s)	00-06	06-12	12-18	18-24	00-24
L	0.0238	0.0982	0.3021	0.1217	0.5458
S	0.0416	0.1336	0.2272	0.1474	0.5498
U	0.0335	0.0656	0.4010	0.1822	0.6823
LS	0.0033	0.0284	0.0182	0.0099	0.0598
LU	0.0106	0.0270	0.0578	0.0182	0.1136
SU	0.0033	0.0129	0.0269	0.0437	0.0868
LSU	0.0009	0.0039	0.0087	0.0025	0.016

SECTION 9
FADE DURATION DISTRIBUTIONS

At fixed attenuation level, what is interesting is the number of events that exceed a specific time duration. Distributions for each of the three sites in Tampa and for Waltham, at levels of 2, 8 and 16 dB, are shown in Figures 9-1 through 9-4. Except in the tail region, the distributions are well approximated by log-normal distributions. (See Lin (1973)). Table 9-1 lists the scaled medians and standard deviations of these distributions for the Tampa sites.

At each of the attenuation levels nearly the same median and standard deviations were obtained for the three Tampa sites. Since the distributions shown are for long observation periods, these single-site fade distributions, like the attenuation distributions, tend to lose inter-site differences.

Table 9-1

Fade Duration Distributions: Medians and Standard Deviations - Tampa -

Attenuation Level and Site		Time (Min) Corresponding To Median	Standard Deviation* (of Log Duration)
2 dB	L	9.98	0.47
	U	8.55	0.52
	S	9.57	0.49
8 dB	L	3.45	0.54
	U	2.51	0.65
	S	3.34	0.55
16 dB	L	1.71	0.62
	U	1.52	0.69
	S	1.81	0.63

*These parameters may be used as follows, for example, at S: At the 8 dB level, the duration 50% of the time is 3.34 minutes but ranges from 0.9 to 11.9 minutes in plus or minus one standard deviation.

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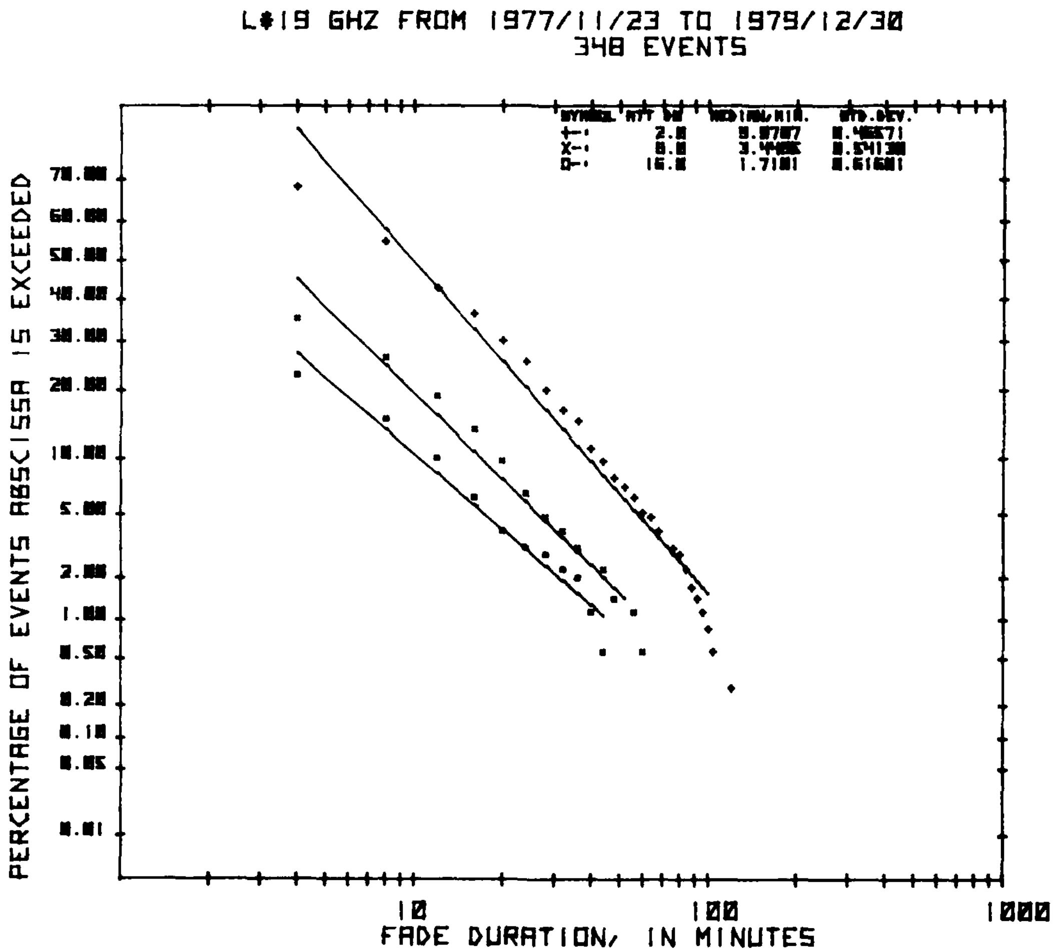

Figure 9-1. Fade Durations, 19 GHz, Lutz, 348 Events, 1977-1979

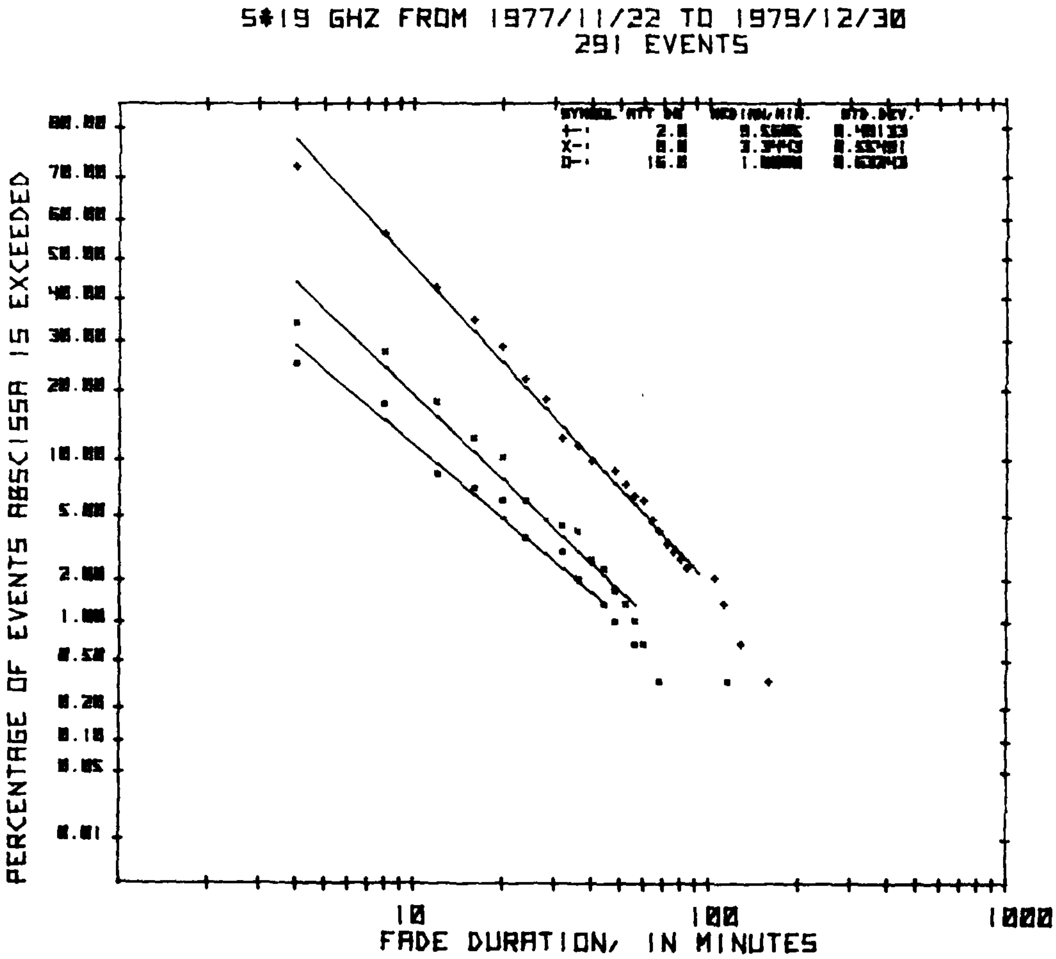

Figure 9-2. Fade Durations, 19 GHz, Sweetwater, 291 Events, 1977-1979

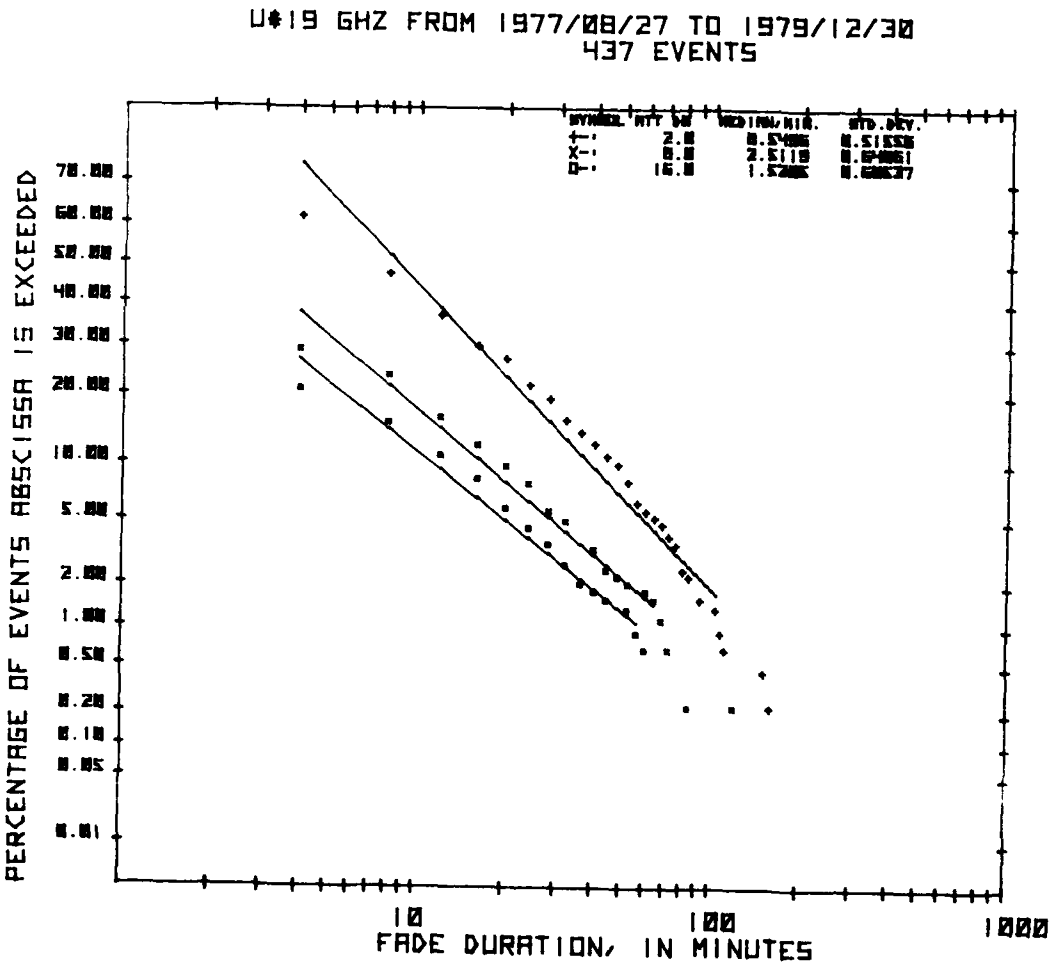

Figure 9-3. Fade Durations, 19 GHz, USF, 437 Events, 1977-1979

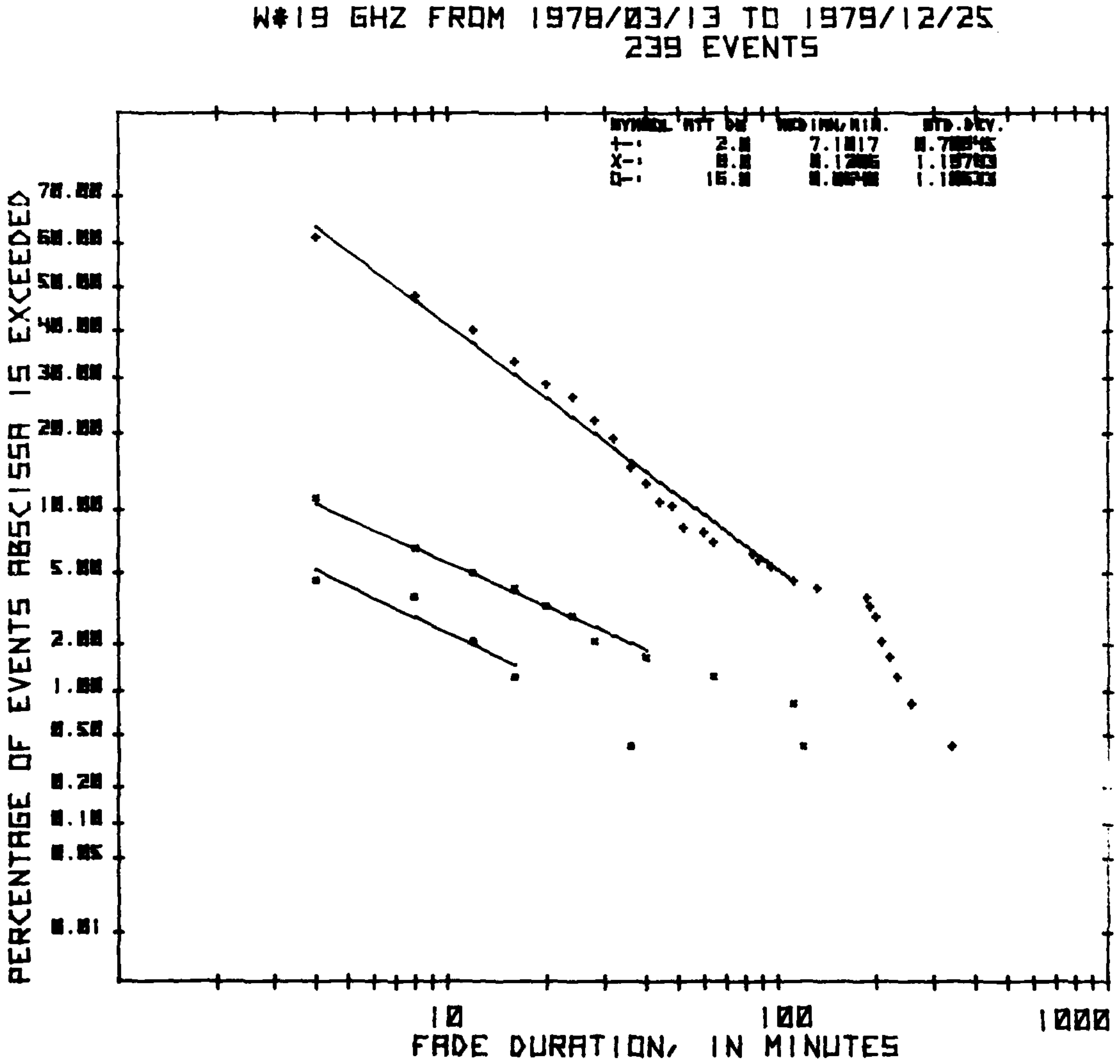

Figure 9-4. Fade Durations, 19 GHz, Waltham, 239 Events, 1978-1979

SECTION 10
RAIN-RATE DISTRIBUTIONS

Two different types of rain gauges have been used to measure rainfall at the Tampa sites: The capacitance-type rain-rate gauge (Belfort manufacture) and the tipping-bucket type (Weathermeasure manufacture). The output voltage of the capacitance gauge is proportional to rain rate, but the relationship is not linear. Rain rates corresponding to 0.2 volt steps, from 0.2 to 0.4 volts, were read from calibration curves supplied by the manufacturer with each unit and were used in preparing the exceedance distributions. The tipping-bucket gauge makes a contact closure for every 0.01-inch rainfall accumulation (0.25 mm). The computations necessary to derive rain rate from the record of closures are described by Nackoney (1979).

In Waltham only the tipping-bucket gauge was used, and the output pulses were recorded on digital (magnetic) tape with an HP9825A desk-top calculator. Rain rates were computed for a selected integration time, usually for one minute.

Initially only capacitance gauges were used in Tampa; tipping-bucket gauges were installed later: at U, on January 29, 1979; and May 1, 1979 for L and S. It was not possible to record the tipping-bucket output pulses at the Tampa sites because of calculator system limitations. Thus, only the total rain falls were available from the tipping-bucket gauges.

Once the exceedance distributions based on the capacitance-gauge measurements were obtained, an integration of the curve yields the total rainfall. Though the rainfall obtained with the two instrument types should in the end be identical or nearly so, in practice they have not been. Table 10-1 lists the total rainfall as measured in these two ways for Tampa; the Waltham results were obtained from tipping bucket only.

In Tampa, large differences between the two methods were found for some months. For instance, for U, March and September; for S, May and September; and for L, December. At U, the capacitance gauge result was too low for March and too high for September. At L, the gauge gave too low a result. And at S, the results were low for the two months named. Yet examination of the available analog charts revealed no outstanding irregularities. Rain rate, it will be recalled is recorded continuously on an analog chart in parallel with the rain attenuation. The tipping-bucket closures show up as ticks on the envelope of the rain rate recording. Higher analog rain rate always corresponds to denser ticks.

Table 10-1

Monthly Total Rainfall (1979) in Inches, as Measured with Capacitor-Type Rain-Rate Gauge and Tipping-Bucket-Type Rainfall Gauge

Site:	U		L		S		W	
Method:	A	B	A	B	A	B	C	B
January	4.8	NA	5.1	NA	2.9	5.7*	11.2	9.7
February	3.0	2.88	2.5	NA	1.4	2.9*	2.0	3.0
March	1.0	4.08	12.28	NA	2.5	2.4*	1.8	2.6
April	0.9	0.59	2.23	NA	0.2	0.6*	4.1	4.4
May	15.3	16.78	12.2	16.78	5.1	15.67	4.5	4.5
June	3.8	4.80	2.6	1.24	1.1	0.67	2.5	1.5
July	3.4	5.16	3.8	6.84	9.8	8.72	3.5	3.0
August	13.2	11.93	13.5	18.9	11.7	18.36	5.0	4.4
September	31.1	16.42	10.6	16.96	4.4	13.77	2.8	2.8
October	- - -	- - - -	- NO RAIN	- -	- - -	- - - -	2.5	2.3
November	1.4	1.16	4.1	2.92	1.1	1.19	2.0	2.2
December	0.9	1.53	5.3	1.53	2.6	2.04	0.5	0.9

Notes: *Official rainfall at Tampa International Airport, 1.6 km southwest of Sweetwater.

A: Total rainfall obtained by integrating the rain-rate exceedance distribution obtained with capacitor-type rain-rate gauge.

B: Total rainfall via tipping-bucket rain gauge.

C: Total rainfall obtained by integrating the rain-rate exceedance distribution obtained by differentiation of tipping bucket output with time.

After examining the two instruments, it was concluded that the total rainfall as measured by the tipping bucket gauge is more accurate than that obtained by integrating the rain rate exceedance curve obtained from the capacitance gauge. Four factors affect the accuracy of the capacitance gauge: (A) <u>Clogging</u> of the water-chute by insects (dead or alive). When the water-chute is clogged, it limits the ability of the gauge to measure high rain rates. Regular weekly cleaning alleviates this problem but does not eliminate it completely. (B) Finite drying-out time. Since the water-chute cannot dry out instantly upon cessation of rainfall, the actual measured raining time is longer, depending on how long it takes for the water-chute to dry-out. (C) Spillover, or the inability to confine rain water entirely inside the chute without spillover at high rain rates. (D) Compression at low rain rate, or the inability to measure accurately rain rates under 50 mm/hr. For rain rates under 50 mm/hr, the calibration curve exhibits some random variations. (On May 30, 1981, a large funnel with three times the original rain collecting area was installed at each site to improve accuracy in low rain rates.)

Since the total rainfall is the only common parameter between the two gauges, the rainfall obtained with the tipping bucket may be used to generate a calibration factor. When all rain rates measured with the capacitance gauge are multiplied by this factor, and the resultant exceedance curve is integrated, the total rainfall so obtained will be the same as that obtained by the tipping bucket. This calibration process has been applied on a monthly basis.

Figure 10-1A shows Tampa Triad rain rate exceedance curves obtained for May 1979 without calibration, and Figure 10-1B shows those curves when calibrated. Figure 10-2 and Figure 10-3 show rain-rate exceedance curves for the five summer months and the year 1979 obtained from the calibrated monthly curves. For comparison purposes, NWC (National Weather Center), five-minute rain-rate distributions are shown as starred points, and the rain-rate distributions for Region E in the global model as proposed by Crane is shown as solid line in Figure 10-3. The mean annual rainfall in Tampa is 1219 mm and a total of 1689 mm rainfall was recorded at Tampa Airport by NWC, 4[illegible] mm more than for an average year. One standard deviation in annual rainfall (based on 40 years of data) is 290 mm. Thus in 1979, Tampa's rainfall was about 1.6 standard deviations above the mean. Figure 10-4 and 10-5 are the rain-rate distributions obtained in Waltham. For comparison, National Weather Center five-minute rain-rate distributions are shown as starred points, and the rain-rate distribution for Region D2 in the Crane model is shown as solid line. The average annual rainfall in Boston is 1074 mm and a total of 1122 mm was recorded by NWC, indicating close to an average year for 1979 in Boston. The five-minute rain-rate distributions were prepared actually from the published NWC hourly precipitation data using the empirical method suggested by Lin (1975).

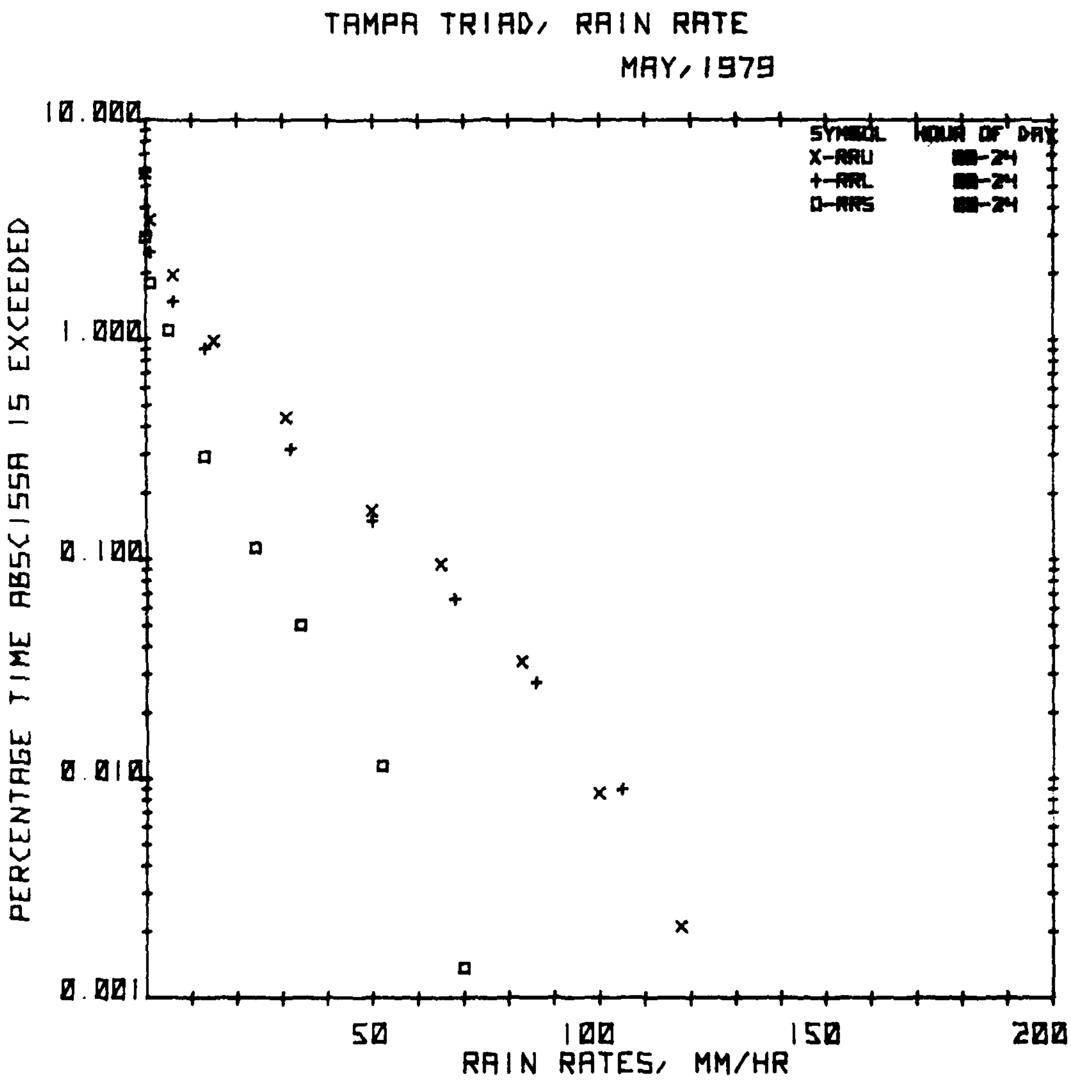

Figure 10-1A. Rain Rate Distributions, Tampa, May 1979

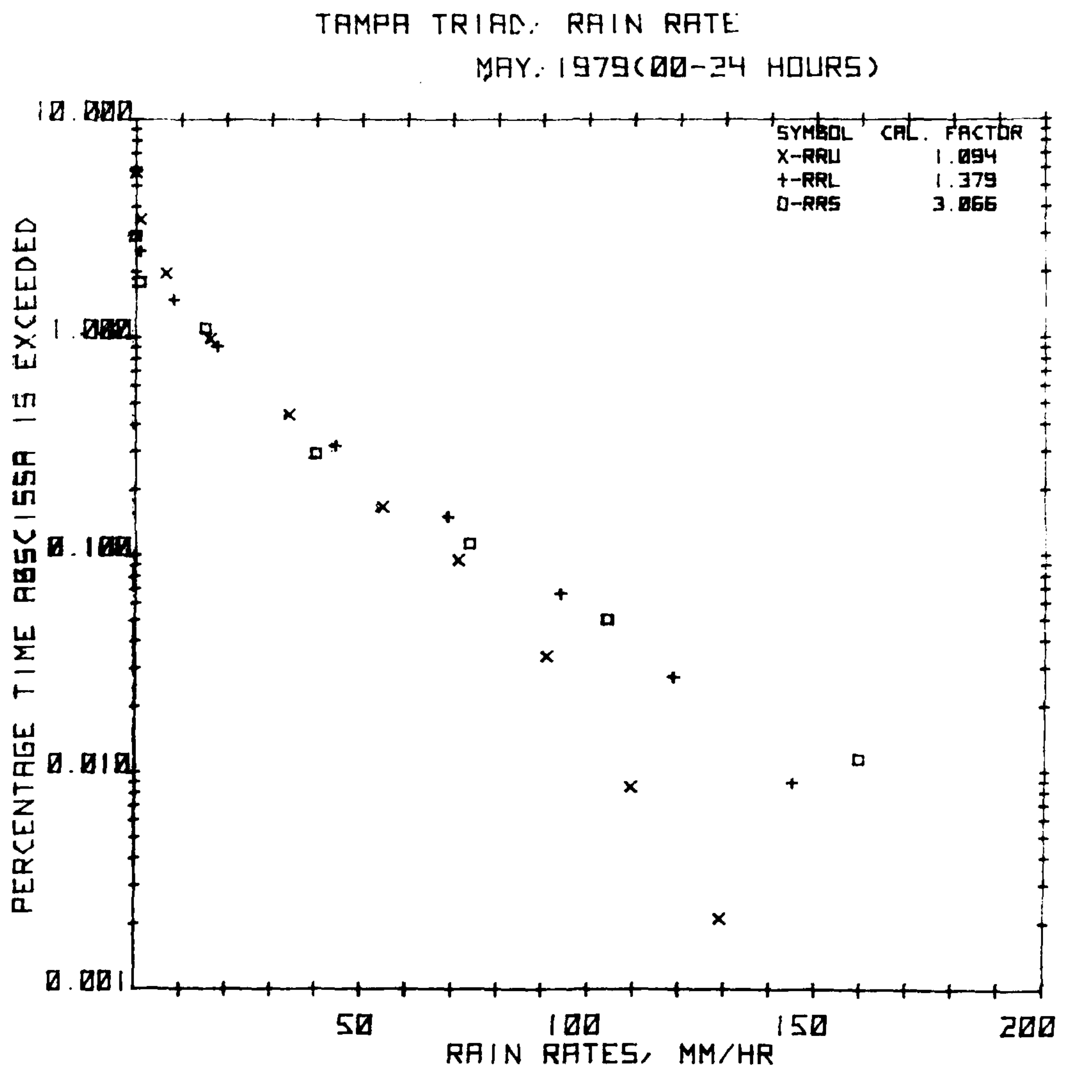

Figure 10-1B. Rain Rate Distributions (Adjusted), Tampa, May 1979

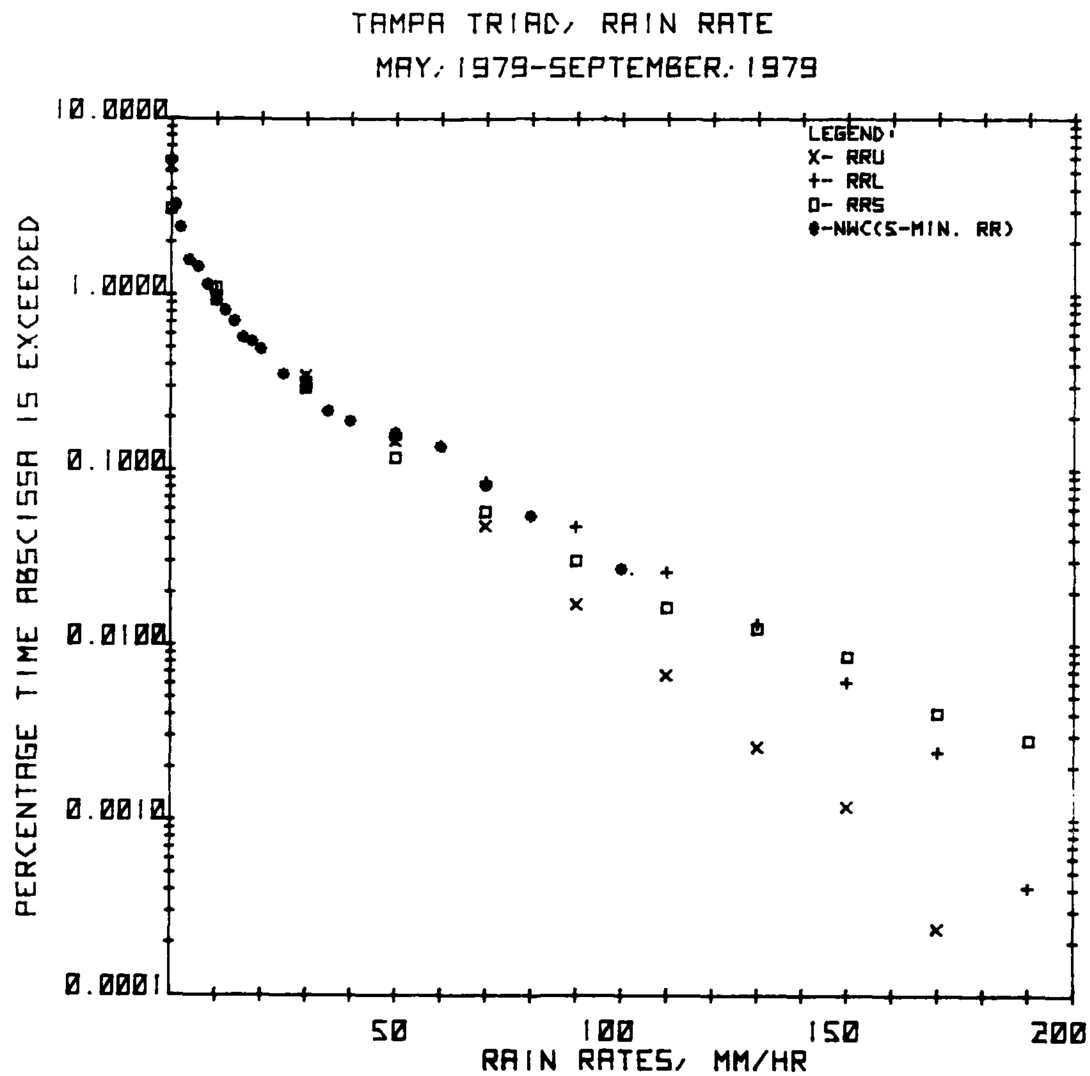

Figure 10-2. Rain Rates, Tampa, May-Sept 1979, Including NWC Data

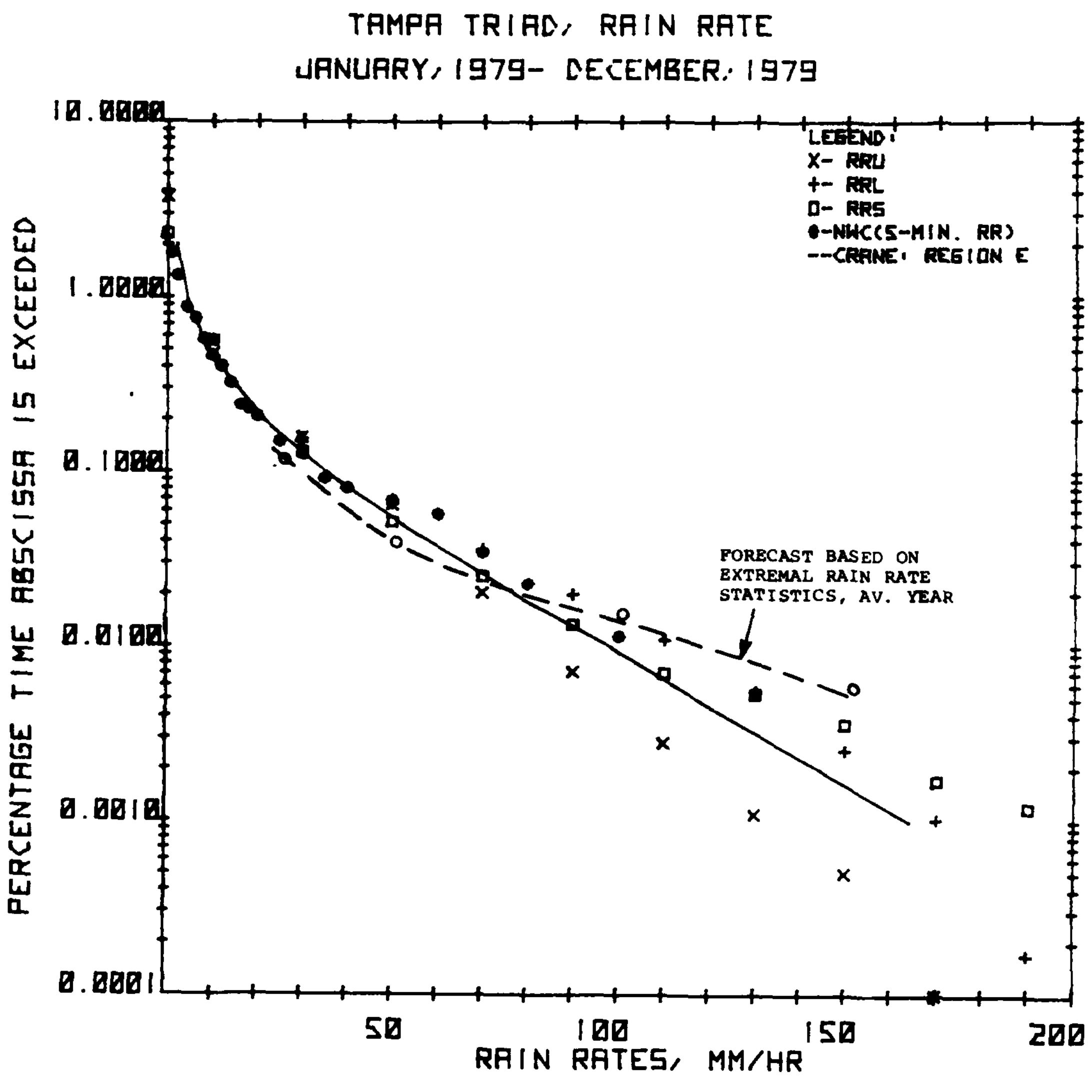

Figure 10-3. Rain Rates, Tampa, 1979, With Comparisons as Indicated

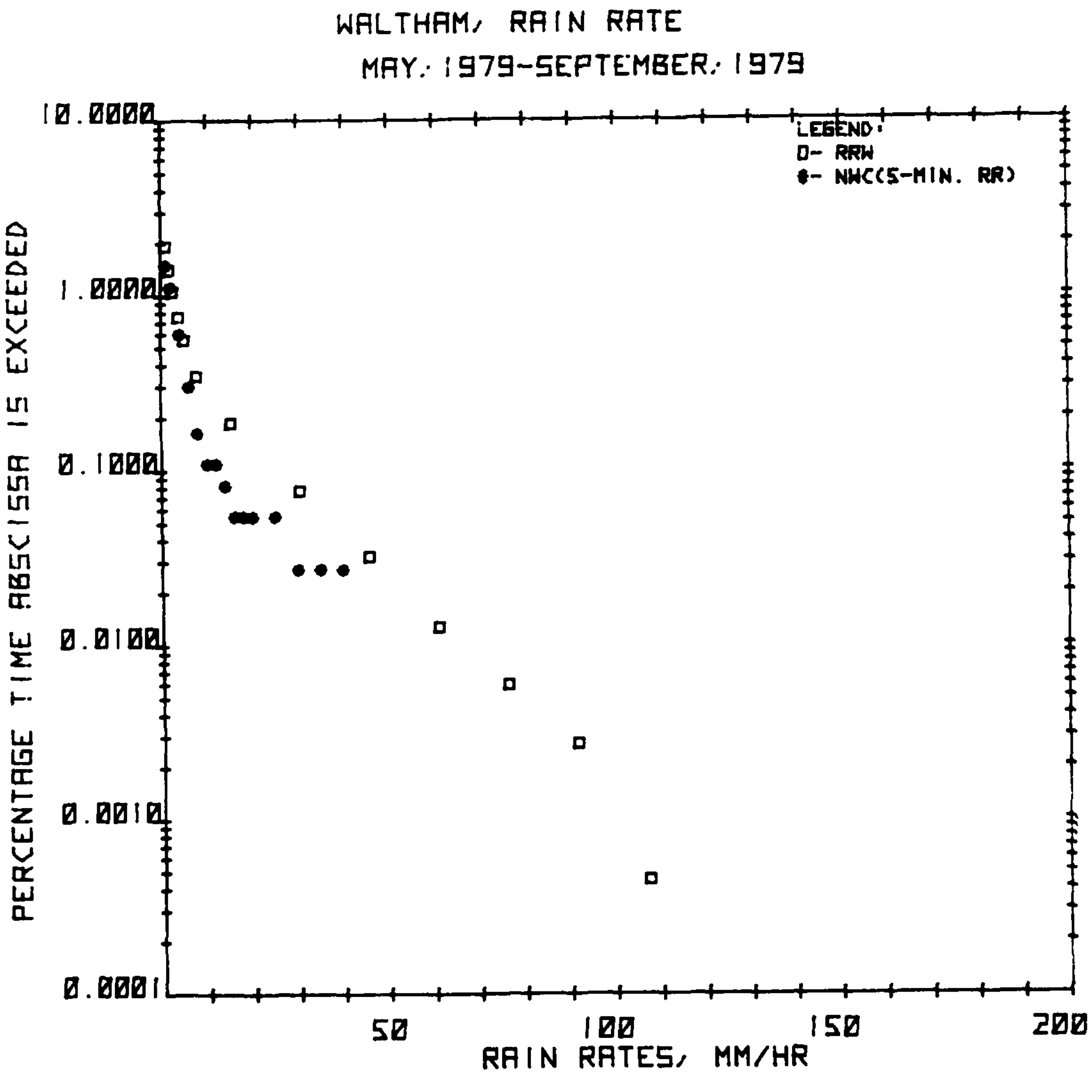

Figure 10-4. Rain Rate, Waltham, May-Sept 1979, With Boston NWC Data

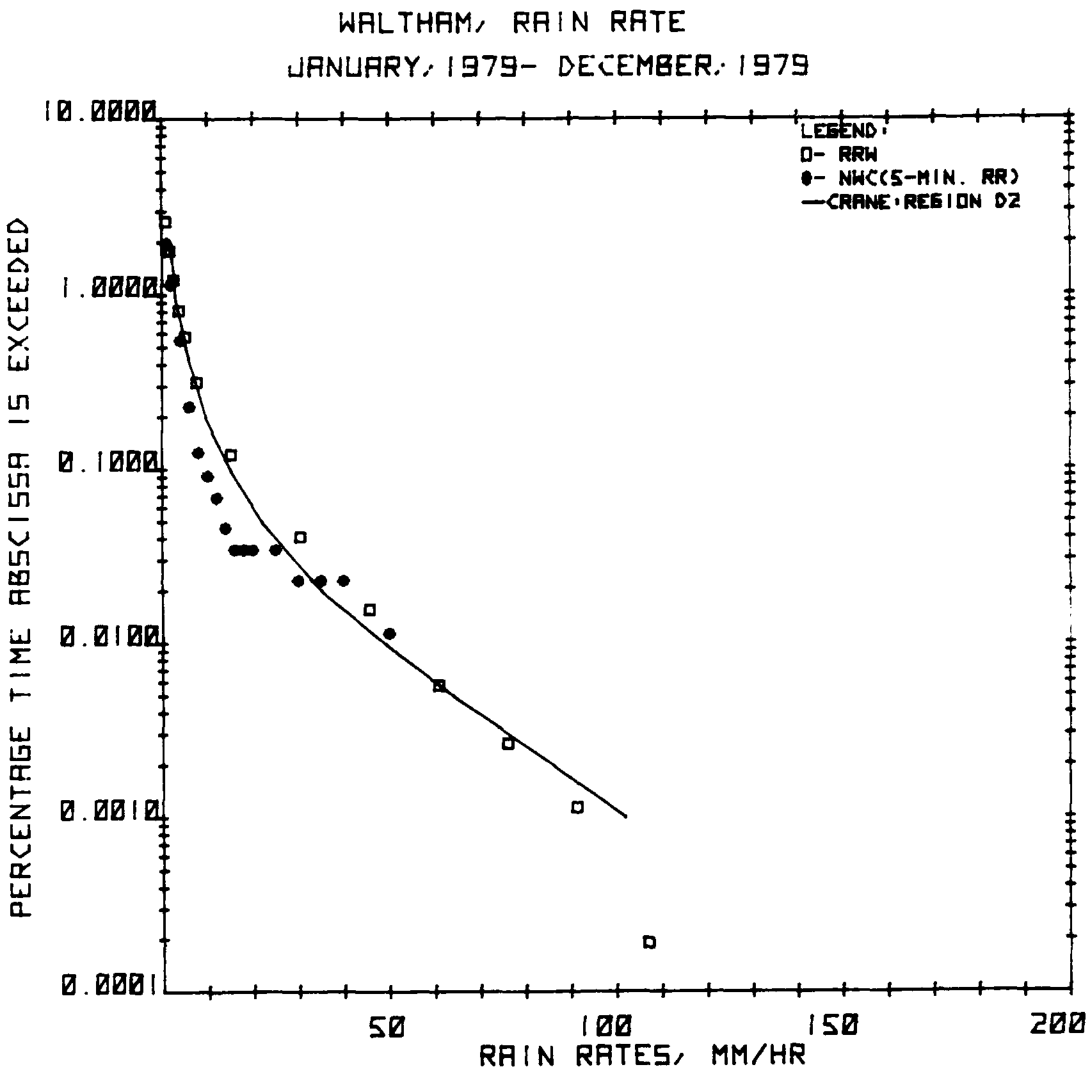

Figure 10-5. Rain Rate, Waltham, 1979, With Boston NWC Data and Region D2 Model

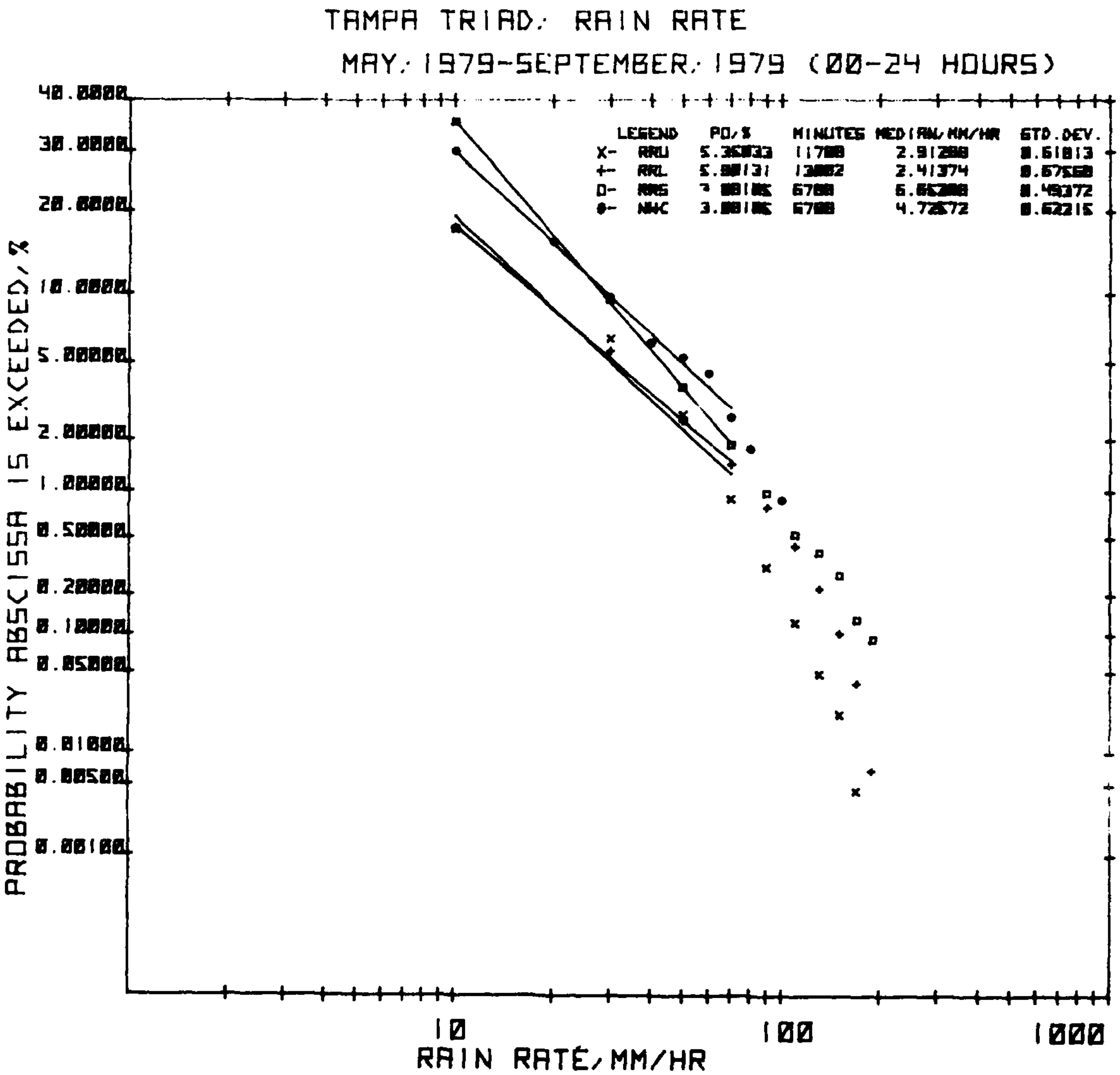

Figure 10-6. Rain Rates, Tampa, May-Sept 1979. Lognormal Basis.

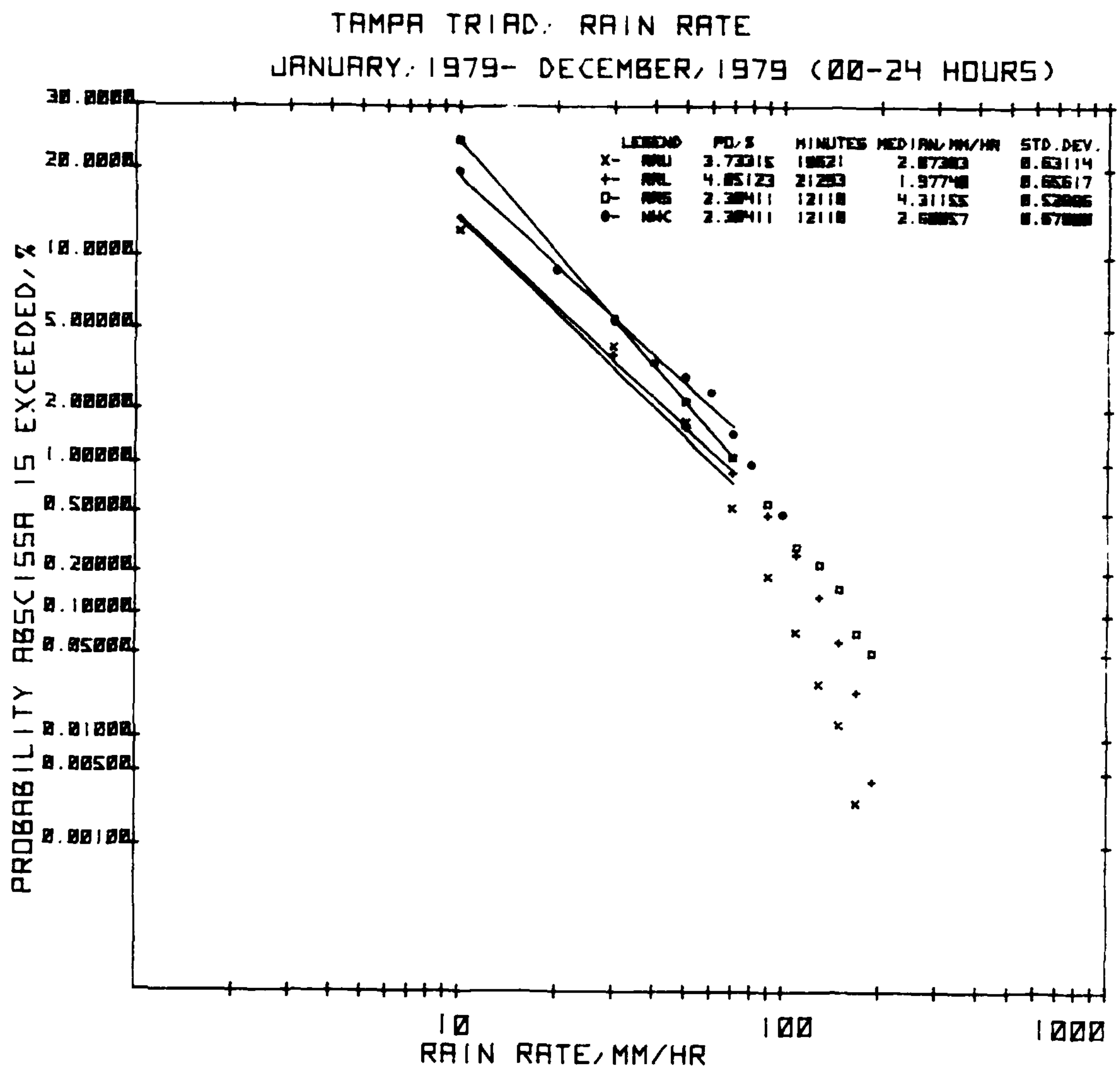

Figure 10-7. Rain Rates, Tampa, 1979. Lognormal Basis.

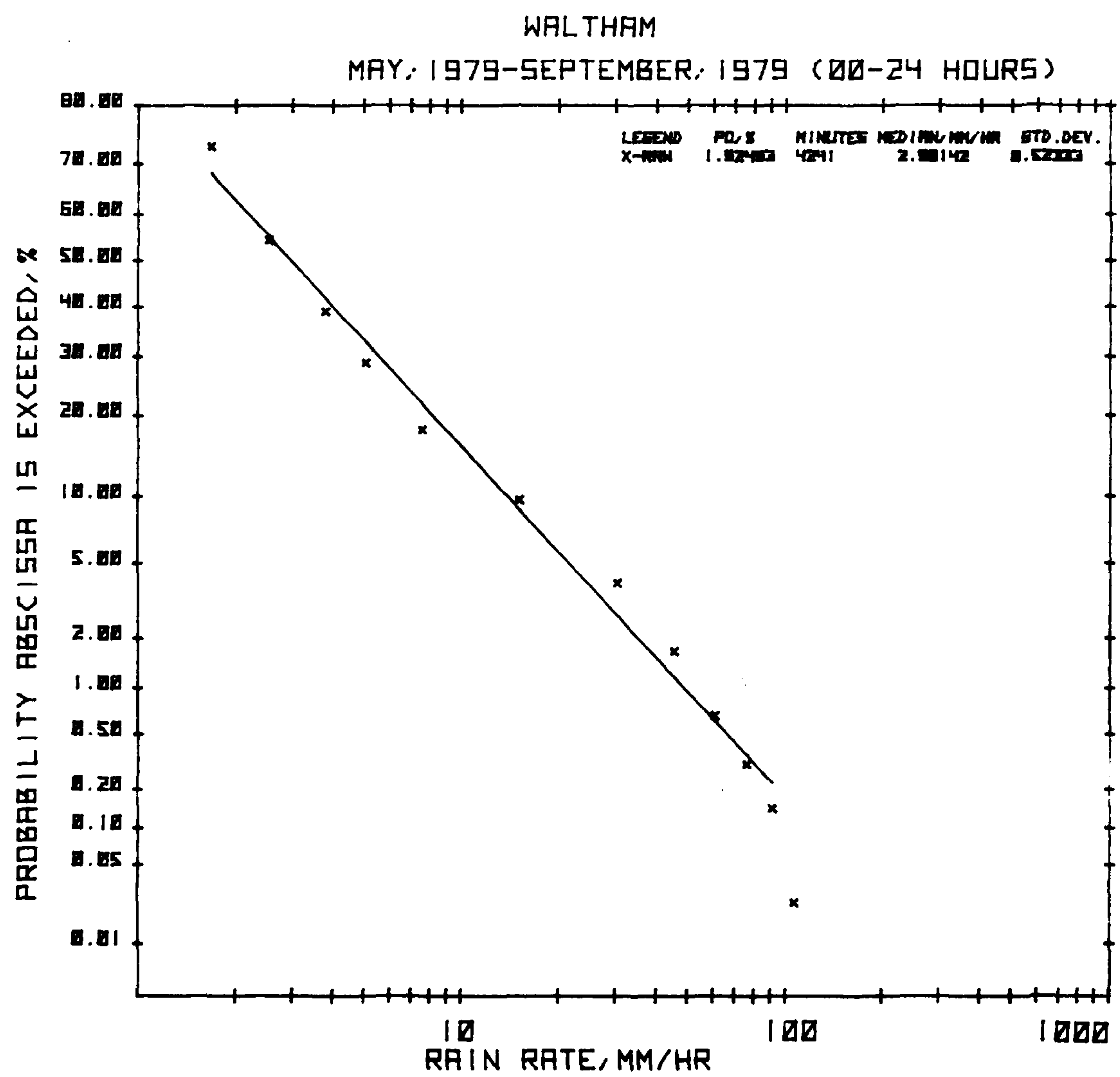

Figure 10-8. Rain Rate, Waltham, May-Sept 1979. Lognormal Basis.

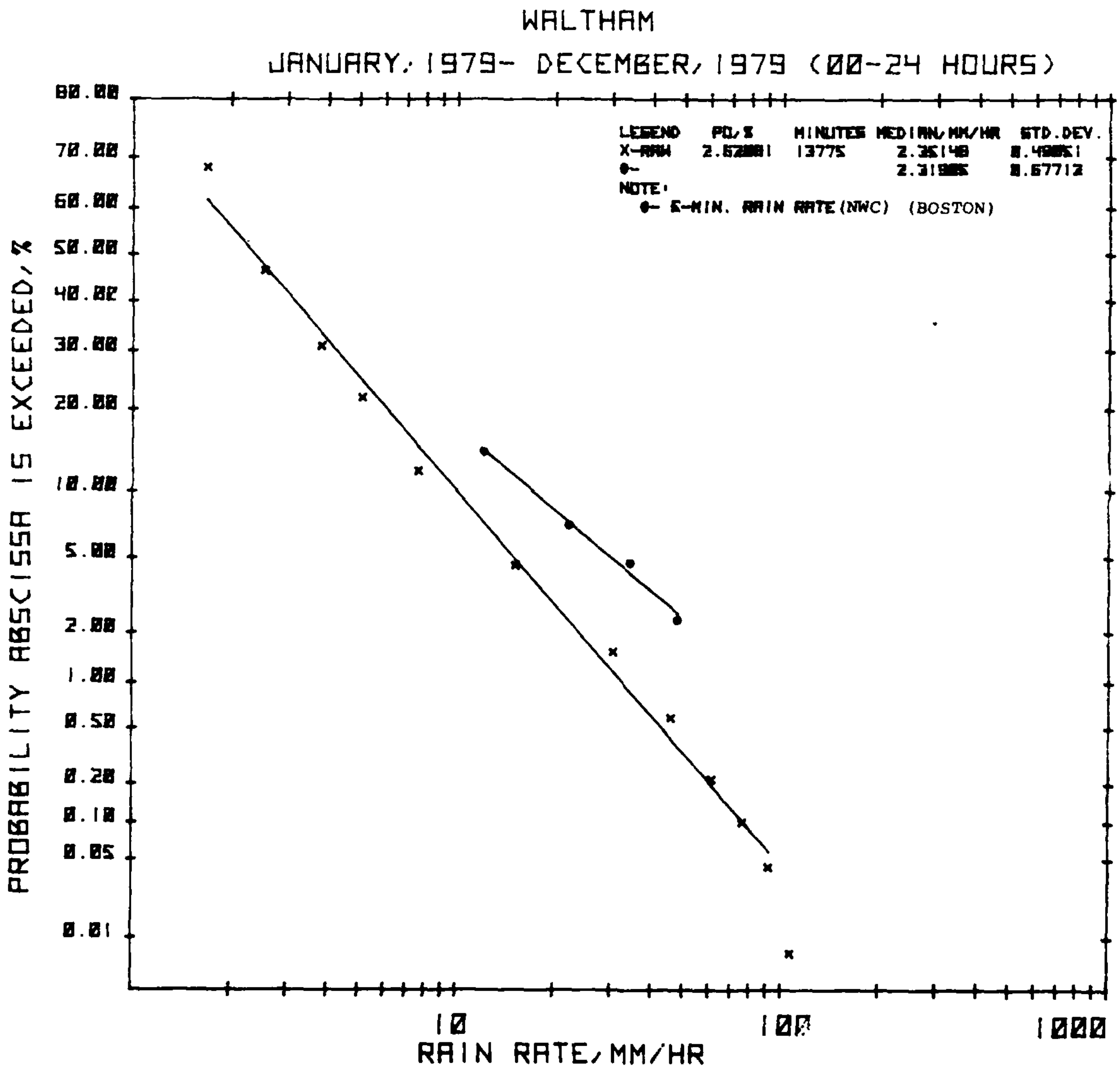

Figure 10-9. Rain Rate, Waltham, 1979. Lognormal Basis.

From Figures 10-2 through 10-5, it was possible to generate log-normal distribution fits, as shown in Figures 10-6 through 10-9. However, there is a break in the log-normal fit. For Tampa, this break is at 70 mm/hr for all sites, including NWC data; for Waltham, it is at 90 mm/hr. The rain rate distribution can be fitted by two log-normal lines, joined together at the break. The median and standard deviations are for the low-rain fit. Similar observations were reported by Morita (1980) for rain-rate distributions measured at three locations in Japan. The break points reported were 42 mm/hr in Akita, 60 mm/hr in Tokyo and 42 mm/hr in Shionomisaki. The two-segment log-normal distributions correspond to light rain and heavy rain.

To test a log-normal fit, it is necessary to identify some rain rate above which a rain event is said to occur. That is, a fractional time P_o must be defined to relate raining time to total observation in Section 6. In the present case for rain rate, raining was defined as the time during which rain rate exceeded 1 mm/hr in both Tampa and Waltham. On this basis the log-normal fits shown in Figures 10-6 through 10-9 were obtained.

The average, μ, is related to the median and standard deviation of a log-normal distribution by:

$$\mu = \exp\left[m/K + (1/2)(s/K)^2\right] \qquad (10\text{-}1)$$

where

m = mean of log R

s = standard deviation

K = log e = 0.4343

Using Equation 10-1, the mean rain rate can be calculated as shown in Table 10-2.

The average rain rate can also be estimated from the NWC tabulations by using P_o' the fraction (days per year) rain of any kind was observed by at least one tip of a tipping bucket gauge, and the total yearly rainfall, W, we put $R_o = W/kP_o'T_o$ where T_o = 8760 hours/year and k is a fraction estimator that estimates $P_o = kP_o'$ for a five minute integration time. From Lin (1975), $k \cong 0.5$ for relating probability for one-hour to one-minute integration times. In Table 10-3, k = 0.2 is used to reduce from one-day integration time to five-minute integration time [rate rate at one-minute integration is higher than for five-minute integration by a factor of about 1.3. (Nackoney, 1980)]

Table 10-2

MEAN RAIN RATE (mm/hr)

	May to September	January to December
USF	8.0	6.0
Lutz	8.1	6.2
Sweetwater	12.7	9.0
NWC Tampa Airport	13.2	8.5
Waltham	6.2	4.4
NWC Boston	-	7.8

Compare P_o in Table 10-3 for 1979 with the corresponding P_o shown in Figures 10-6 through 10-9. For Tampa, $P_o = 0.06$ in the Table while in the figure, $0.023 \leq P_o \leq 0.041$, and for Waltham, $P_o = 0.07$ in the table and $P_o = 0.026$ in the figure.

For 1979, however, the three-site average rain rate from the figure in Tampa is 7.1 mm/hr while that from table is 3.2 mm/hr. The NWC station in Tampa is located at the airport which is only about 1.6 km from Sweetwater. The mean rain rates obtained at Sweetwater and NWC Airport station are very close, 9 mm/hr and 8.5 mm/hr respectively. At Waltham, the mean rates are 4.4 mm/hr from the figure and 1.8 mm/hr from the table.

Table 10-3

Estimate of Average Annual 5-min Rainfall (k=0.2)

	1979 No. Days w/Rain	$P_o = kP'_o$	Mean W	1979 W	R_o (Average)	Mean No. Days w/Rain (39 years)
Tampa	104	0.06	1219	1689 mm	3.2 mm/hr	107
Boston	131	0.07	1074	1122	1.8	128

Note that for Tampa in 1979, although the number of days with rain was close to average, the total rainfall in those days was much above average (1689 vs. 1219 mm).

SECTION 11

COMPARISON WITH ATTENUATION PREDICTIONS

11.1 CRANE MODEL

Crane (1980) has developed a model for predicting rain attenuation on satellite links from a given base of rain rate statistics. This model is a refined version of Crane's earlier model (1978).

Crane has been mainly interested in applying modeling "globally", such that its (input) rain statistics are distributions representing various rain climate regions. Other features of the Crane model are its effective-path algorithm, and inclusion of a statistical description of the 0°C isotherm height, this height being necessary to truncate the liquid-water interaction region on the path to the satellite.

In using Crane's model we have made one change. Most of the locations of interest to us are well-known U.S. cities (or sites nearby) at which long series of rain-rate measurements have been made by NWC and its predecessor, the U.S. Weather Bureau. Using this NWC data Dutton-Dougherty (D-D) (1979) developed maps with 1-min rain-rate isoclines in average year for P = 1%, 0.1% and 0.01% of the time, together with similar maps for the related standard deviations. While D-D's figures have been utilized by Crane in developing his rain climate rain-rate representations for USA, Crane also utilized many measurement results and spatial smoothing. We have preferred to use the applicable D-D rain rates for specific sites.* For in-between choices of P we have chosen to interpolate using a quadratic fit in log P.

Figure 11-1 shows comparison of the Tampa 1979 calendar year data with our version of Crane's model, for average year and standard deviations σ = 1, 2. The prediction underestimates attenuation at high attenuation (high rain rate), for the σ = 1.6 case. (σ = 1.6 is approximate: Tampa rainfall for 1979 was above average, about 1.6 standard deviation from average).

A similar computation was made for Waltham as shown in Figure 11-2, applying Boston statistics (the Boston NWC measurement site is about 22 km east of Waltham), for an average year. (Boston rainfall was close to average for 1979). Here the agreement is much better in the tail region because the rain rates are lower. In the model the Boston rain rate at P = 0.01% was 50 mm/hr, for Tampa it was 110 mm/hr in average year.

*On another occasion we have checked D-D's values for several cities using NWC/USWB data and found general agreement except in one instance (Seattle) at the P = 0.01% level.

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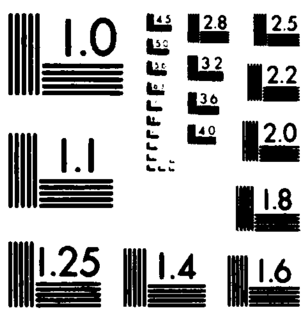

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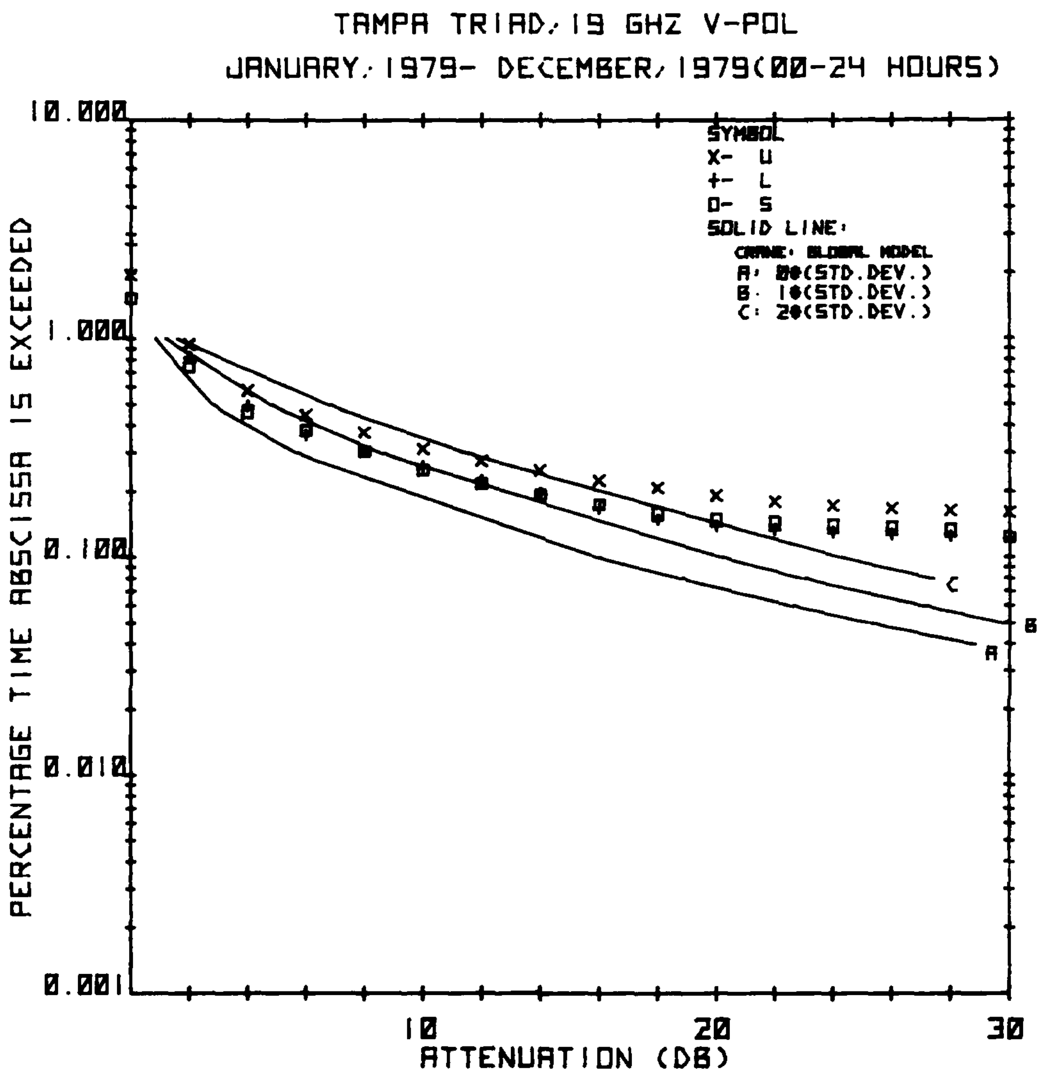

Figure 11-1. Attenuations, 19 GHz, Tampa. Comparison With Crane Model.

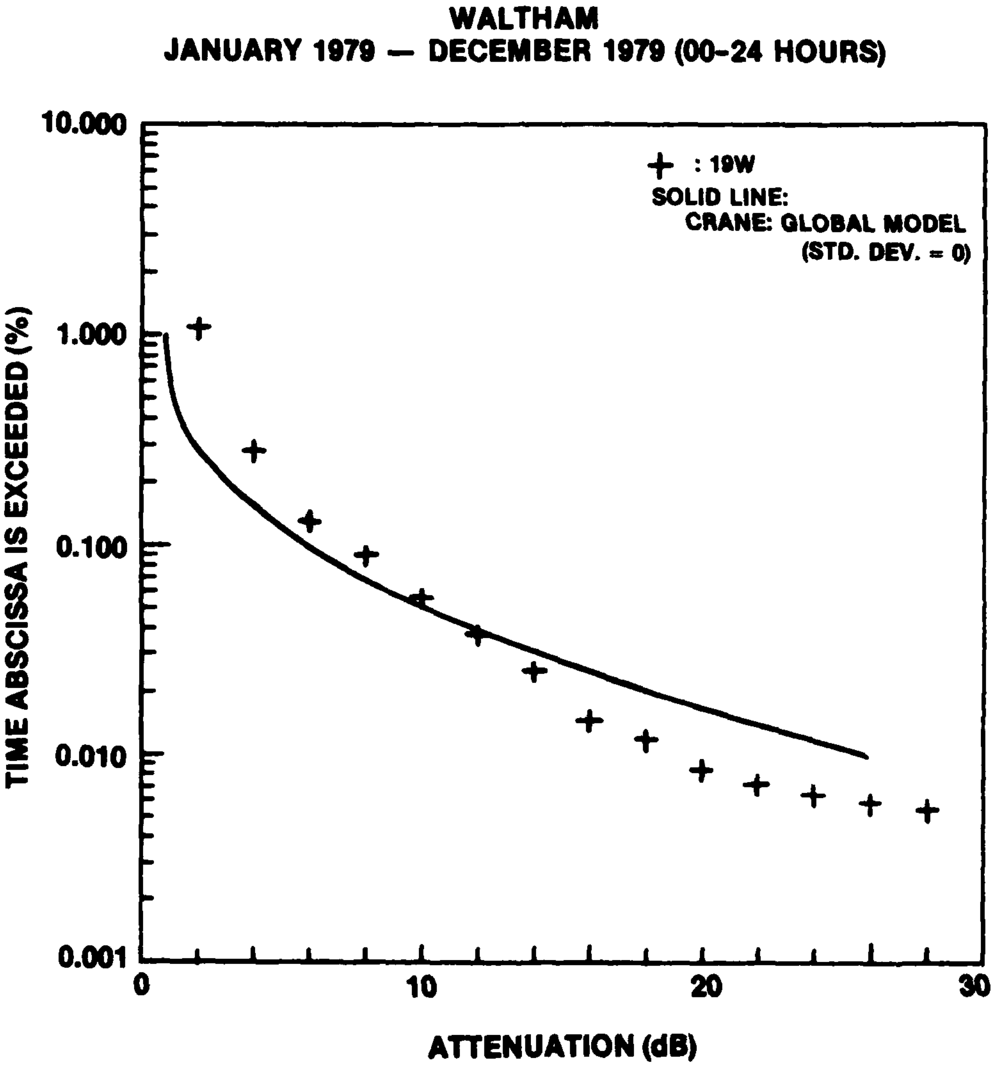

Figure 11-2. Attenuations, 19 GHz, Waltham. Comparison With Crane Model.

11.2 THE DIFFERENCES BETWEEN MODELS AND EXPERIMENTS

One possible source of elevated attenuation has been identified in the papers of Dissanayake and McEwan (1978) and Watson (1978): This is the so-called enhanced attenuation in the "bright-band", the region noted in radar sensing where liquid is first formed from snow. Watson shows that the attenuation ratio for 30 and 20 GHz, A_{30}/A_{20}, is much higher for ice than for water (equivolumetric basis) and that even a small ice component can influence the ratio significantly. The wide swing in the ratio A_{29}/A_{19} noted in our 1978 Report for specific events (rather than statistically over a long period) could be explained in this way.

Another source of difference between model and experiment is the choice of specific attenuation α(dB/km) in the form $\alpha = aR^b$. This has been discussed in some detail by Olsen, Rogers and Hodge (1978). Crane's latest model uses values of a, b that seem to have differing agreement with those tabulated by Olsen, et. al., depending on the radio frequency. Since we are concerned here with f $\cong$ 20 GHz, we tabulate comparisons in Table 11-1 where we give the a, b pairs from Olsen et. al., at f = 20 GHz for Laws and Parsons (low rain rate = LP_L), high rain (LP_H) and Marshall-Palmer drop distributions for 0°C, and the resulting α for R = 3, 13, 50, 100 mm/hr. Included also are α from Oguchi and Hosoya (1974) for the same R. We see that Crane has apparently fitted his coefficients at this frequency to use LP_L (0°C) for low rain rates and LP_H (0°C) for high rates. (See boxed entries.) This result is evidently faithful to the recommendation of Olsen, et. al. (loc cit). It is likely too that during passage through a thunderstorm cell the beam encounters different temperature regimes giving different attenuation rates, as shown in the tables in Olsen, et. al.

A third source often suggested as accounting for larger-than-expected attenuation at high rain rate in the 20-30 GHz region is increased influence of multiple scattering. A discussion on the issues will be found in Ishimaru and Cheung (1980) where the interest is in relating attenuation calculated from radiometric <u>absorption</u> to that to be experienced in transmission. The authors show that radiometer measurements involve absorption cross-section not extinction, which is the sum of absorption and scattering. But in the calculations used to determine path (specific) <u>attenuation</u> $\alpha = aR^b$, what is used is the extinction cross section $\sigma_{ext} = (4\pi/k^2)S(0)$, with k the wave number and S(0) the forward-scattering ($\theta = 0$) amplitude of the scattered wave. This is discussed in the aR^b paper by Olsen, Rogers and Hodge (1978), and indeed is so treated in the fundamental work of Van de Hulst (1957). So excess attenuation cannot be attributed to multiple scattering. [Relative contributions of absorption and scattering are tabulated by Setzer (1970)].

TABLE 11-1

a, b AND ATTENUATIONS α FOR f = 20 GHz

	Coefficients		α			
	a	b	R=3	13	50	100 mm/h
Crane (1978)	0.0695	1.0985	0.2322	1.163	5.11	10.94
LP_H (0°)	0.0626	1.119	0.2140	1.104	$\boxed{4.99}$	$\boxed{10.83}$
LP_L (0°)	0.0709	1.083	$\boxed{0.233}$	$\boxed{1.140}$	4.91	10.39
MP (0°)	0.0719	1.097	0.240	1.199	5.25	11.24
LP_H (20°)	0.0859	1.044	0.271	1.250	5.10	10.52
LP_L (20°)	0.0683	1.111	0.232	1.180	5.27	11.39
MP (20°)	0.0751	1.103	0.252	1.272	5.62	12.07
Oguchi*	0.0776	1.033	0.242	1.099	4.43	9.06
Crane (1978)	0.0600	1.091	0.199	0.983	4.27	9.09

*Vertical Polarization

SECTION 12
CONCLUSIONS

Beacon reception studies on 19 and 29 GHz continuing into 1979 and 1980 have provided a rather substantial data base indicating the severity of problem rain attenuation in the greater Tampa area, an area characterized by very intense rainfall intervals in afternoons in summer months. Tampa rain attenuation distributions show a flattish tail, not common to observations elsewhere, due to the extremely rapid rate-of-change of rain attenuation at onset and recovery. Our Waltham experience with the same reception equipment, and indeed our experience in the fall or winter months in Tampa confirms that this is a characteristic of Tampa summer data.

Diversity results indicate that for the baselines studied, 11-20 km, there is significant improvement with diversity pairs for baselines exceeding 16 km, but that the improvement is still not quite sufficient to provide reliable annualized performance at the 0.01%/10 dB level. Three-site diversity is very promising but can only be provided at the cost of more complexity. Still, for the future, when fibre-optic links will link local telephone exchanges, triple diversity may be the strategy that will enable 19/29 GHz satellite links to be used for trunking purposes, for terminals in the Tampa area or areas like it.

This study could be extended, absent any downlink signals for reception measurements, by operating synchronized rain gauges at the two sites L and S and two other sites located to the east, making baselines in excess of the longest (20 km) we used. These rain gauge measurements should well indicate diversity performance for these longer baselines for satellite links that operate with high elevation angle, a feature to be desired in any planned SHF satellite communication system terminating in intense rain areas.

SECTION 13

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APPENDIX

RAIN FADING AND SYSTEM PERFORMANCE

In Section 2 and elsewhere in this report we have used a 10-dB rain attenuation fade as a point of reference for assessing propagation reliability. To establish the practicality of this fade margin, the amount of tolerated fading in relation to the system margin is determined by a full-link analysis that considers (1) the go and return halves of a circuit; and (2) all sources of impairments, not just fading and the attendant increase in antenna temperature. A convenient starting point is given in a paper by Davidson and Zahalka (1979). That paper develops the thermal noise contributions of uplink and downlink relative to the total thermal noise, under various fading conditions, taking into account (1) the compression introduced by the satellite transponder;* and (2) the attenuation ratio, uplink-to-downlink. In this report we are considering systems operating in the 20/30 GHz paired bands, and based on the general trends of our Florida and Waltham measurements, as well as those of Bell Labs in Georgia, we shall in the discussion that follows assume a nominal 30/20 GHz attenuation ratio of two. Without sacrificing generality, we shall also assume the same transponder characteristic of the reference paper, but we shall assume a clear-weather system temperature of 125K, a value that we believe will ultimately be attainable in the 20-GHz band.

CCIR Recommendation 522 (Kyoto 1978) prescribes the bit error rate (BER) limit for PCM telephony as no more than 10^{-6} (ten-minute mean value) for no more than 20% of any month. The same recommendation notes that "any" month is construed to mean the "median worst month of the year", based on the set of months for which statistics are available (thus, the "worst month" discussion in Section 4 of this report).

A modem meeting this requirement in satellite service might have the characteristics shown in Table A-1. Assuming that thermal noise constitutes half the channel noise, the carrier-to-noise (C/N) ratio for non-thermal contributors ought then to be 19.0 dB, so that the result comes out to be 16.0 dB (as in the table).

*No signal processing in the satellite.

Recommendation 522 also recommends that the BER not exceed 10^{-4} for more than 0.3% of any month. This decrease in allowed BER permits reduction of 2 dB in C/N, from 16.0 to 14.0 dB at threshold.

But since non-thermal contributions are fixed, the allowed thermal noise at threshold comes to C/N = 15.7 dB.

To find the requisite uplink and downlink C/N, we must compute the margin factors D, U, T, given in the referenced papers. These depend on the downlink attenuation, the attenuation ratio, and the compression characteristic of the satellite transponder (assumed to be similar to those operating at lower bands). These factors are added to the clear-sky threshold carrier/noise ratio to determine the relative C/N contributions.

Table A-2 shows these factors for a 0-12 dB rain attenuation range. Note the severe requirement on the uplink factor U for downlink attenuation over 10 dB. U is sensitive to attenuation ratio; had the ratio been taken as 1.64, the value used in the original studies at 12/14 GHz, the 10-dB attenuation entry for U would have been only 19.3 dB.

Any system capable of handling a 10-dB rain fade would have to start with a 14.7 dB downlink margin above threshold (per link) and the uplink C/N would have to be about 47.9 dB (U = 31.9, $(C/N)_{Th}$ = 16.0) at fade time, which would probably be at the limit of present satellite system capabilities without diversity.

The behavior is best depicted in Figures A-1 and A-2. The C/N plane is shown in Figure A-1, while the circuit margins above threshold are shown in Figure A-2 for a 10-dB downlink fade as downlink attenuation varies between zero and threshold fade level.

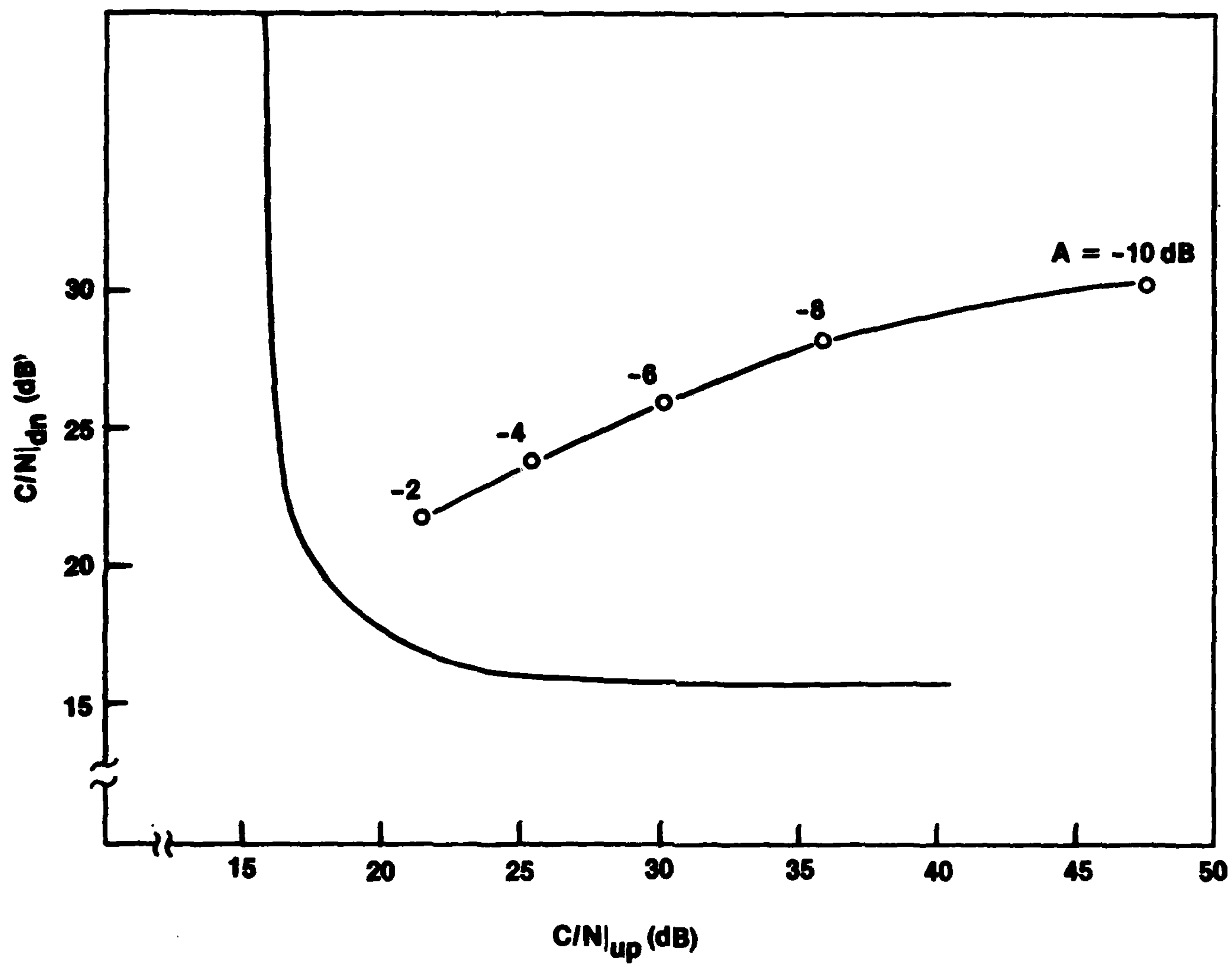

Figure A-1. Fade Locus of 20/30 GHz System in the Plane Defined by the Uplink and Downlink Carrier-to-Noise Ratios.

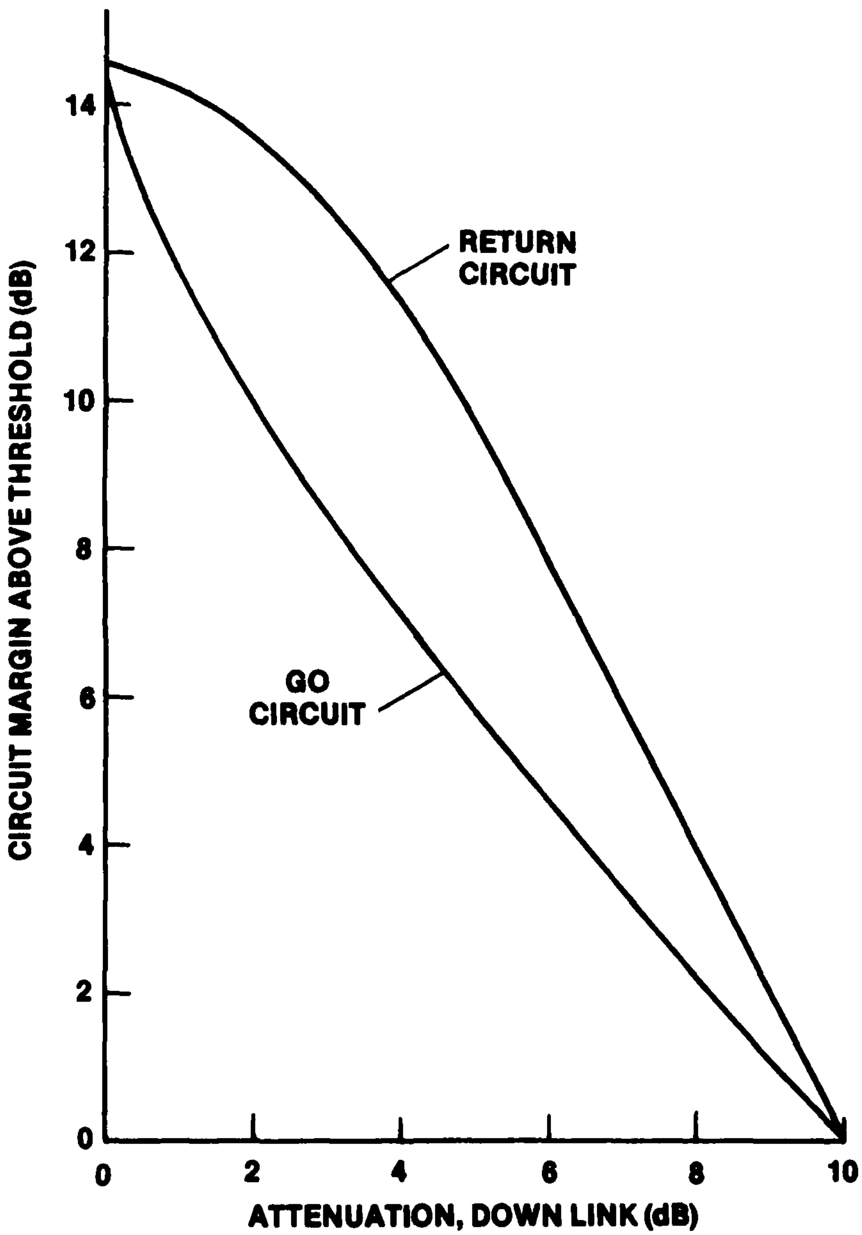

Figure A-2. Margin Above Threshold for Go and Return Circuits vs Downlink Fade.

Table A-1

Carrier/Noise Ratio Requirement for QPSK
Showing Impairment Sources

E_b/N_o, ideal coherent PSK, BER = 10^{-6}	10.5 dB
Convolutional decoding	0.3
Implementation allowance	1.0
Satellite filters and non-linearities	1.0
Earth station filters, non-linearities	1.0
Net E_b/N_o	13.8
QPSK bit-rate/channel bandwidth	3.0
Filter loss	0.8
C/N (Total)	16.0

Table A-2

U, D, T Factors For Attenuation Ratio = 2
T_s = 125°K, n(A → ∞) = 3.63

A (dB	D (dB)	U (dB)	T (dB)
0	3.8	2.1	0.0
2	6.0	5.6	2.8
4	8.1	9.7	5.8
6	10.3	14.4	8.9
8	12.6	20.1	11.9
10	14.7	31.9	14.6
12	16.8	-	-

(n represents the effective compression characteristic of the transponder)

APPENDIX 2

PUBLICATIONS AND PAPERS

Grant DAAG29-77-G-0224

Experience with COMSTAR Beacon Receiving Triad in Tampa, Florida.
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APPENDIX 3

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